REQUIREI) BANDWIDTH, UNWANTED EMISSION AND DATA POWER EFFICIENCY FOR RESIDUAL AND SUPPRESSED CARRIER SYSTEMS -A COMPARATIVE STUDY[1]-

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ABSTRACT

This paper presents a new concept for required bandwidth along with a method for computing this bandwidth and associated unwanted emission for the classes of PCM/PSK/PM, PCM/PM and BPSK signals. The PCM/PSK/PM signals considered here employ either a squarewave or sinewave subcarriers with NRZ data format, On the other hand, the PCM/PM and BPSK signals usc either a Bi-phase or NRZ data format. Furthermore, the optimum required bandwidth in the presence of noise and the data power efficiency among these modulation schemes will also be investigated. The term "data power efficiency" considered in this paper consists of two principle components, namely, the amount of power contained in the data channel, and the Symbol Signal-to-Noise Ratio (SSNR) degradation duc to the presence of InterSymbol interference (1S1) for a specified required bandwidth. This paper evaluates both of these components numerically and the results are then compared among the modulation schemes considered.

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10 INTRODUCTION

As the presently allocated frequency bands become more congested, it is imperative that the most bandwidth-efficient communication methods be utilized. Additionally, space agencies arc under constant pressure to reduce costs. Budget constraints result in simpler spacecraft carrying less communications capability as well as reduced staffing at the earth stations used to capture the data. Therefore, the power-efficiency of each modulation scheme becomes an important discriminator in the evaluation process.

The topic of bandwidth for the space telemetry signals has been investigated in great detail in the recent past [1-2]. The space telemetry signals examined in [1-2] employed both residual and suppressed carrier modulation techniques, and additionally, these papers only evaluated the Occupied Bandwidth of the transmitted signal. 'his paper presents a new concept for the required bandwidth along with a method to calculate this bandwidth and the associated unwanted emission for PCM/PSK/PM signals with squarewave and sinewave subcarriers, PCM/PM and BPSK with both NRZ and Bi-phase data formats. The data power efficiency for these modulation techniques will also be evaluated and compared. As mentioned earlier, the term "power data efficiency" considered here includes the effects of 1S1 on the Symbol Error Rate (SER) performance degradation, In addition, the results for the optimum bandwidth in the presence of noise will also be presented and compared with the others.

Traditionally, space agencies have employed subcarriers for both telecommand and telemetry data transmissions, Subcarriers provided a simple method for separating different types of data as well as ensuring no overlap between the modulated data's frequency spectra and the RF carrier. Mathematically, he signal can be expressed by

$$s_1(t) = \sqrt{2}\, A \sin[\omega_c t + \text{red}(t)\ \ P(t)] \tag{1}$$

where A* is the power, ω_c is the angular carrier center frequency in rads/see, m is the modulation index in radian, d(t) is the NRZ binary valued data sequence with symbol period T, and P(t) is the subcarrier waveform. Expanding Eqn (1) onc obtains

$$s_1(t) = \sqrt{2}\, A[\sin(\omega_c t)\cos(mP(t)) + d(t)\cos(\omega_c t)\sin(mP(t))] \quad (2)$$

The signal expressed in Eqn (2) is usually called PCM/PSK/PM signal, and the subcarrier waveforms recommended by the international Consultative Committee for Space Data Systems (CCSDS) arc the squarewave and sinewave for deep space and near earth missions, respectively [3]. Hence, onc has PCM/PSK/PM-Squarewave and PCM/PSK/PM-Sinewave for squarewave and sinewave subcarriers, respectively. Currently, the CCSDS has expressed considerable interest in eliminating the subcarrier to conserve bandwidth. The transmitting signal format without the subcarrier becomes PCM/PM. The mathematical expression for PCM/PM signal is given by

$$s_2(t) = \sqrt{2}\, A\sin[\omega_c t \cdot md\, t)] \quad (3)$$

Expanding Eqn (3) we get:

$$s^*(t) = \sqrt{2}\, A[\sin(\omega_c t\ \mathrm{Cos}\ m) + d(t)\cos\ \omega_c t)\sin(m)] \quad (4)$$

where the data sequence d(t) can be formatted either in the form of NRZ or Bi-phase (or Bi-ϕ). Therefore, one has PCM/PM/NRZ and PCM/PM/Bi-phase for NRZ and Bi-phase data formats, respectively,

The mathematical expression for suppressed carrier modulation, namely BPSK signal, is defined as follow

$$s_3(t) = \sqrt{2}\, Ad(t)\sin[\omega_c t] \quad (5)$$

again, the data sequence d(t) can be either NRZ or Bi-phase. Thus, one has BPSK/NRZ and

13 PSK/Bi-phase for NRZ and Bi-phase data formats, respectively. In the following sections, the terms required bandwidth as well as unwanted emissions will be defined and a method for calculating these quantities will be presented. Moreover, the optimum bandwidth in the presence of noise and the data power efficiency will also be investigated in detail.

This paper is organized in the following manner. Section 2 defines the term “required bandwidth” and presents a method to calculate this quantity for various modulation schemes mentioned above. Section 3 explains the term “unwanted emission” and shows how this quantity can be computed. The data power efficiency is considered in Section 4. The term data power efficiency calculated in this section consists of two components, namely, the power contained in the data channel for the required bandwidths of 2/T and 4/T (Where T denotes the symbol period), and the symbol SNR degradation in the data channel for various values of required bandwidths. Section 5 shows how to calculate the optimum required bandwidth in the presence of white Gaussian noise. The discussions and main conclusions are presented in Sections 6 and 7, respectively.

2. REQ UIRED BANDWIDTH: DEFINITION AND ANALYSIS

2,1 INTRODUCTION AND DEFINITION OF REQUIRED BANDWIDTH

Several years ago, the International Telecommunications Union (ITU) established criteria for quantifying the bandwidth used by a telecommunications system. Termed “Occupied Bandwidth,” Regulation RR- 147, of the ITU's Radio Regulations defined the term as [4]:

> “Occupied Bandwidth: the width of a frequency band such that, below the lower and above the upper frequency limits, the mean power emitted are each equal to a specified percentage $\beta/2$ of the total mean power of a given emission,
>
> Unless otherwise specified by the international Radio Consultative Committee (CCIR) for

the appropriate class of emission, the value of $\beta/2$ should be taken as 0.5 %."

Under the ITU definition, the Occupied Bandwidth is that span of frequencies which contains 99 % of the emitted power. Where digital communications are concerned, Occupied Bandwidths of unfiltered signals tend to be very large, especially for PCM/PSK/PM signals [1].

The ITU Radio Regulations also contain an alternative definition called Necessary Bandwidth. Regulation RR-146 defines the Necessary bandwidth as [4]:

"Necessary Bandwidth: for a given class of emission, the width of the frequency band which is just sufficient to ensure the transmission of information at the rate and with the quality required under the specified conditions. "

Here, the problem is onc of uncertainty. To a large extent "quality" is a subjective concept, Using Necessary bandwidth definition is difficult without a specific standard. Moreover, no attention is paid to power efficiency which would satisfy the requirements of both space and terrestrial communications systems. Generally, Necessary Bandwidth is not deemed to be a useful measure for space telecommunications systems.

Given the problems with both the occupied bandwidth and the necessary bandwidth notions, this paper proposes a ncw measure called the required bandwidth. The principle difference is that a more realistic value for the percentage of power is selected. The proposed definition is:

"Required Bandwidth: For a specific type of modulation, the width of the frequency band such that, below the lower and above the upper frequency limits, the mean power emitted are each equal to 2.5 percent of the total unfiltered, ideally modulated digital data spectrum, using the same "modulation scheme."

Note that this definition is not referenced to 99 % of the power in the transmitted spectrum as is for the Occupied Bandwidth. That is because spectrum control is inherent in the concept of required bandwidth. In simple terms, required bandwidth is that bandwidth needed to complete a communication with an acceptable amount of power loss. For example, a 5 % decrease in power corresponds to -0.2 dB. Such a reduction should be acceptable to most space missions. Yet, the bandwidth required to send identical messages over two channels, one using Occupied Bandwidth definition and other employing the new required bandwidth definition, will be several times less in later channel when compared to the former, As will be demonstrated in the remainder of this paper, accepting a small loss in system's performance, dramatically reduces the amount of bandwidth needed to complete the communication.

It is assumed that some spectrum shaping will be employed at an appropriate location in the information transmission system so that only the required bandwidth is transmitted from the spacecraft. Figure 1 is a simplified block diagram of a spacecraft Radio Frequency Subsystem (RFS). Note that spectrum shaping can be located in the ranging channel, at the input to the modulator, and at the output of the power amplifier. Spectrum shaping is found on most current spacecraft. All of the spectrum shaping devices shown in Figure 1 may not be required. The actual number and their locations will depend upon the specific RFS design and the linearity of the multiplier and the power amplifier. Obviously, it is desirable to avoid spectrum shaping at the output of the power amplifier because of the RF power loss and increased weight, If the spectrum shaping is done at an earlier point, then the losses resulting from spectrum shaping at the transmitter's output can be largely avoided.

Coherent turnaround and one-way ranging signals present unique problems in Required bandwidth systems. To achieve the desired measurement accuracy, ranging tones sometimes have frequency components, and hence required bandwidths, which are larger than those needed for telemetry and telecommand operations. Since many space missions need all of these services, the RFS depicted in Figure 1 must accommodate the separate spectral requirements imposed by the different services. Clearly, the mechanization of the flight radio system may depend upon a mission's specific requirements.

Fortunately, the system depicted in Figure should permit the flexibility to meet the needs of all services. Moreover, even if the Necessary Bandwidth increases during ranging operations, these sessions are usually concluded quickly so that the increased bandwidth requirement is of short duration.

2,2 ANALYSIS

The required bandwidth for several modulation schemesare calculated in this section. The modulation methods investigated in this paper arc discussed in Section 1 and listed in Table 1. Modulation methods listed in Table 1 are shown in the order of increasing bandwidth efficiency (diminishing required bandwidth). As it will be shown later in Table 2 that in order to compare the required bandwidths for several modulation schemes, power transfer efficiencies of 9070 and 95 % arc used. As noted previously, these correspond to power loss of 0.45 dB and 0.2 dB respective] y.

Figure 2 shows the frequency spectrum of each of the several modulation schemes shown in Table 1, Figure 2 (a) shows the frequency spectrum of a system employing a single squarewave subcarrier. Limited space restricted the ability to show the full spectrum. Odd harmonics of the subcarrier's frequency, each with data sidebands, will be present with diminishing amplitude as the order increases. Figure 2 (b) depict the frequency spectrum Of a system utilizing a single sinewave subcarrier. Unlike the squarewave subcarrier's frequency spectrum, a sinewave subcarrier will have energy at even harmonics in the form of a Delta function. The Delta function's amplitude will depend upon the RF carrier's modulation index. It is this energy that is lost during the demodulation process and which accounts for the lower efficiency of sinewave subcarrier systems.

From a spectrum bandwidth perspective, direct modulation with a Bi-ϕ format is a compromise between direct modulation with an NRZ data format and a conventional subcarrier telemetry system. It places the modulated data sidebands closer to the RF carrier while providing a null in the data's frequency spectrum at the RF carrier's frequency. Figure 2 (c) shows the PCM/PM/Bi-ϕ spectrum which ensures that the carrier will be easily distinguishable from the surrounding data sidebands. The bandwidth advantage of direct modulation schemes is readily apparent in this figure, Direct NRZ differs from Direct Bi-ϕ modulation in that the double frequency clock component is absent in the former modulation type. Here, the modulated binary data's frequency spectrum is discernible narrower than the one for Bi-ϕ modulation. The RF frequency spectrum for PCM/PM/NRZ is shown in Figure 2 (d).

BPSK/Bi-ϕ modulation fully suppresses the RF carrier by modulo-2 adding the data on to a squarewave clock at twice the data symbol's frequency and modulating the RF carrier with an index of 90 degrees. The BPSK/Bi-ϕ spectrum is shown in Figure 2 (e). Like direct residual carrier modulation, BPSK/NRZ differs from BPSK/Bi-ϕ in that the double frequency clock component is absent in the former modulation type. The modulated signal's frequency spectrum for BPSK/NRZ is shown in Figure 2 (f).

Table 1. Investigated Modulation Schemes

Modulation Type	**Description**
PCM/PSK/PM Squarewave	NRZ data is PSK modulated on a squarewave subcarrier which is then phase modulated on the RF carrier,
PCM/PSK/PM Sinewave	NRZ data is PSK modulated on a sinewave subcarrier which is then phase modulated on the RF carrier.
PCM/PM/Bi-ϕ	Data is Bi-phase (Manchester) modulated directly on a residual RF carrier.
BPSK/Bi-ϕ	Data is Bi-phase (Manchester) modulated on an RF carrier fully suppressing it.
PCM/PM/NRZ	NRZ data is phase modulated directly on a residual RF carrier.
BPSK/NRZ	NRZ data is phase modulated directly on an RF carrier fully suppressing it.

2.2.1 REQUIRED BANDWIDTH FOR PCM/PSK/PM WITH SQUAREWAVE

When P(t) is a unit power squarewave subcarrier of frequency f_{sc}, it has been shown in [1] that the required bandwidth for this case is given by

$$\frac{8\sin^2(m)}{\pi^3} \sum_{k\geq 1} \frac{1}{(2k-1)^2} \int_{-\pi(M-n(2K-1))}^{\pi(M-n(2K-1))} [\sin(x)/x]^2 \, dx + \cos^2(m) = p\% \qquad (6)$$

Where M is the normalized required bandwidth (one-sided bandwidth, BW_1) with p% power containment-to-symbol rate ratio (R,), i.e.,

$$M = BW_1/R_s \qquad (7)$$

and n is the subcarrier frequency-to-symbol rate ratio, i.e.,

$$n = f_{sc}/R_s, \text{ where } n \text{ is integer and } R_s = 1/T \text{ is the data rate} \qquad (8)$$

and p% is the percentage of power containment in the signal component. The plot of Eqn (6) for various values of n and m is shown in Figure 3. This figure shows the power containment as a function of the one-sided bandwidth-to-symbol rate ratio. As an example, for 99 % power containment, the one-sided bandwidth is about $328R_s$ for m = 1.2 rad and n = 9 [1,2,3], While, form Figure 1, the one-sided bandwidth for 90 % only requires about $29R_s$. Therefore, if 90 % of the power meets the desired link performance margins, then the required bandwidth will be $29R_s$ which is 11 times less than the bandwidth required for 99 % power containment,

2.2.2 REQUIRED BAN I) WIDTH FOR P CM/PSK/PM WITH SINEWAVE

When P(t) is a sinewave subcarrier, it has been shown in [1] that the required bandwidth for this case is given by

$$J_0^2(m) + 2\sum_{k\ \mathrm{even}}^{L} J_k^2(m) + \sum_{h\ \mathrm{odd}}^{L} J_h^2(m)\, a_h(L) = p\,\% \tag{9}$$

where $a_h(L)$ is defined as

$$a_h(L) = \int_{-Lf_{sc}}^{Lf_{sc}} [S_d(f-hf_{sc}) + S_d(f+hf_{sc})]\,df \tag{10}$$

Here f_{sc} and Lf_{sc} are defined as nR_s and the required bandwidth with p% power containment, respectively. The required one-sided bandwidth BW_2-to-symbol rate ratio is found to be

$$M_2 = BW_2/R_s = Ln \tag{11}$$

Note that $S_d(t)$ is the Power Spectral Density (PSD) for NRZ data which is defined as

$$S_d(f) = T\,\frac{\sin^2(\pi f T)}{(\pi f T)^2} \tag{12}$$

where T is the symbol period, Figure 4 illustrates a plot of Eqn (9) for various values of n and m. This figure shows that, for n = 9, m = 1.2 rad, the required one-sided bandwidth for 90 % power containment is about $9R_s$. On the other hand, the required bandwidth for 99 % power containment is about $27R_s$ which is 3 times greater than the bandwidth required for 90 % power containment.

2,2.3 REQUIRED BAND WIDTH FOR PCM/PM WITH BI-PHASE DATA FORMAT

From Eqn (4), the PSD of the PCM/PM with Bi-phase data format can be shown to be:

$$S_2(f) = \cos^2(m)\,\delta(f - f_c) + T\sin^2(m)\,\frac{\sin^4(\pi(f-f_c)T/2)}{(\pi(f-f_c)T/2)^2} \tag{13}$$

Using Eqn (13), the required bandwidth can be easily calculated. The relationship between the required bandwidth with p% power containment and the modulation index is found as follow:

$$p\% = \frac{2\sin^2(m)}{\pi}\int_{-M_3\pi/2}^{M_3\pi/2}[\sin^4(x)/x^2]\,dx + \cos^2(m) \tag{14}$$

where

$$M_3 = \frac{BW_3}{R_s} \tag{15}$$

where BW_3 is the required one-sided bandwidth for Bi-phase case. This result is the same as the onc found in [2]. The plot of Eqn (14) is shown in Figure 5 for various values of m. As an example, for m = 1.2 rad, the required bandwidths for 9S % and 99 '70 power containment are $5R_s$ and $26R_s$, respectively.

2.2,4 REQUIRED BANDWIDTH FOR PCM/PM WITH NRZ DATA FORMAT

Again, from Eqn (4), the PSD of the PCM/PM with NRZ data format can bc shown to bc:

$$S_2(f) = \cos^2(m)\,\delta(f - f_c) + T\sin^2(m)\,\frac{\sin^2(\pi(f-f_c)T)}{(\pi(f-f_c)T)^2} \tag{16}$$

Using Eqn (16), the required bandwidth can be easily evaluated. The relationship between the required bandwidth with p% power containment and the modulation index is found to be:

$$p\% = \frac{\sin^2(m)}{\pi}\int_{-M_4\pi}^{M_4\pi}[\sin^2(x)/x^2]\,dx + \cos^2(m) \tag{17}$$

where

$$M_4 = \frac{BW_4}{R_s} \tag{18}$$

Here BW_4 denotes the required one-sided bandwidth for NRZ case. Illustrated in Figure 6 is the plot of Eqn (17). This figure shows the power containment as a function of the normalized bandwidth with the modulation index m as a parameter. For instance, the required bandwidths for 95 % and 99 % power containment are $1.6R_s$ and $9R_s$, respectively, for m = 1,2 rad.

2,2.5 REQUIRED BANDWIDTH FOR BPSK WITH BI-PHASE DATA FORMAT

From Eqn (5), the PSD of the BPSK with Bi-phase data format can be shown to be:

$$S_3(f) = T \frac{\sin^4(\pi(f-f_c)T/2)}{(\pi(f-f_c)T/2)^2} \tag{19}$$

Using Eqn (19), the required bandwidth can be easily evaluated. The relationship between the required bandwidth w th p% power containment is found to be:

$$p\% = \frac{2}{\pi} \int_{-M_5\pi/2}^{M_5\pi/2} [\sin^4 x)/x^2]dx \tag{20}$$

where

$$M_5 = \frac{BW_5}{R_s} \tag{21}$$

here BW_5 is the required one-sided bandwidth for BPSK/Bi-phase case. The plot of Eqn (20) is shown in Figure 7. As an example, the required one-sided bandwidths for 95 % and 99 % power containment are $6.5R_s$ and 31~, respectively.

2.2.6 REQUIRED BANDWIDTH FOR BPSK WITH NRZ DATA FORMAT

Again, from Eqn (5), the PSI) of the BPSK with NRZ data format can be shown to have the following form:

$$S_2(f) = T \frac{\sin^2(\pi(f-f_c)T)}{(\pi(f-f_c)T)^2} \tag{22}$$

Using Eqn (22), the required bandwidth can be computed easily. The relationship between the required bandwidth with p% power containment is given as

$$p\% = \frac{1}{\pi} \int_{-M_6\pi}^{M_6\pi} [\sin^2(x)/x^2]\,dx \tag{23}$$

where

$$M_6 = \frac{BW_6}{R_s} \tag{24}$$

here BW_6 denotes the required one-sided bandwidth for BPSK/NRZ case. Illustrated in Figure 7 is the plot of Eqn (23). This figure shows the power containment as a function of the normalized bandwidth, For example, the required one-sided bandwidths for 95 % and 99 % power containment are $2R_s$ and 11 R_s, respectively.

To compare the required bandwidths for the several modulation schemes listed in Table 1, power transfer efficiencies of 90 % and 95 % are used. Additionally, for comparative purposes, the modulation index, m, of 1.2 radians and subcarrier frequency-to-symbol rate ratio, n, of 9 are used in the calculation of the required bandwidth for the residual systems. Table 2 presents the required bandwidths under these specified conditions for the modulation methods listed in Table 1.

Table 2, Required Bandwidth for the Investigated Modulation Schemes

Modulation Type	90% Power Containment	95% Power Containment
PCM/PSK/PM-Squarewave (n = 9, m = 1.2 rad)	$\pm 30R_s$	$\pm 75R_s$
PCM/PSK/PM-Sinewave (n= 9, m = 1.2 rad)	$\pm 10R_s$	$\pm 10R_s$
PCM/PM/Bi-ϕ (m = 1,2 rad)	$\pm 2.5R_s$	$\pm 5R_s$
PCM/PM/NRZ (m = 1.2 rad)	$\pm 1.2R_s$	$\pm 2.5R_s$
BPSK/Bi-ϕ (m = $\pm\pi/2$)	$\pm 3R_s$	$\pm 6.5R_s$
BPSK/NRZ (m = $\pm\pi/2$)	$\pm 1R_s$	$\pm 2R_s$

"The unwanted emission is the amount of emission such that, below the lower and above the upper frequency limits, the total power contained in the unwanted emission is equal to a percentage of the total power. "

3.2 ANALYSIS FOR THE UNWANTED EMISSION

By definition, the unwanted emission can have both continuous and discrete components. In the followings, the unwanted emission caused by each component will be calculated separately for each type of modulation scheme considered above. Notice that form the PSD, wc observe that only PCM/PSK/PM/sinewave subcarrier have both discrete and continuous components and the rest has only continuous component.

From Eqn (6), the unwanted emission, denote as SE1 %, for PCM/PSK/PM with squarewave subcarrier can be evaluated using the following equation

$$SE1\% = 1 - \frac{8\sin^2(m)}{\pi^3} \sum_{k\geq 1} \frac{1}{(2k-1)^2} \int_{-\pi(M-n(2K-1))}^{\pi(M-n(2K-1))} [\sin(x)/x]^2 dx - \cos^2(m) \tag{25}$$

From Eqn (9), for PCM/PSK/PM with sinewave subcarrier, the unwanted emission due to continuous spectrum, denoted by $SE2_c\%$, is given by

$$SE2_c\% = 1 - J_0^2(m) - 2\sum_{k\ even}^{\infty} J_k^2(m) - \sum_{h\ odd}^{L} J_h^2(m)\, a_h(L) \tag{26}$$

and the unwanted emission, denoted by $SE2_d\%$, due to the discrete component is given by

$$SE2_d\% = 2\sum_{k\ even}^{\infty} J_k^2(m) \tag{27}$$

The unwanted emission for PCM/PM/Bi-phase, denoted by SE3%, can be evaluated by using, from Eqn (14)

$$SE3\% = 1 - \frac{2\sin^2(m)}{\pi} \int_{-M_3\pi/2}^{M_3\pi/2} [\sin^4(x)/x^2]dx - \cos^2(m) \tag{28}$$

From Eqn (17), the unwanted emission for PCM/PM/NRZ, denoted by SE4%, can be evaluated by using, from Eqn (14)

$$SE4\% = 1 - \frac{\sin^2(m)}{\pi} \int_{-M_4\pi}^{M_4\pi} [\sin^2(x)/x^2]dx - \cos^2(m) \tag{29}$$

Similarly, from Eqn (20), the unwanted emission for BPSK/Bi-phase, denoted by SE5%, is given by

$$SE5\% = 1 - \frac{2}{\pi} \int_{-M_5\pi/2}^{M_5\pi/2} [\sin^4(x)/x^2]dx \tag{30}$$

From Eqn (23), the unwanted emission for BPSK/NRZ, denoted by SE6%, is given by

$$SE6\% = 1 - \frac{2}{\pi}\int_{-M_6\pi}^{M_6\pi} [\sin^2(x)/x^2]\,dx \tag{31}$$

The unwanted emission for each modulation type is calculated and the numerical results arc plotted in Figures 8-10. The key results presented in Figure 8-10 are summarized in Table 3. This table shows the results for one-sided bandwidth of $2R_s$ and $4R_s$ for both BPSK and PCM/PM signal with m = 1.3 rad for PCM/PM, and one-sided bandwidth of $20R_s$ for PCM/PSK/PM signals with m = 1.3 rad and n = 3,9. Again, the values of m and n used in these computations are for comparative purpose only.

4, DATA POWER EFFICIENCY

4.1 POWER CONTAINED IN '1'1111 DATA CHANNEL

The power contained in the data channel for a specified bandwidth canbe calculated from the results presented in Section 2. From Eqns (6), (9), (14), (17), (20) and (23), the power contained in the data channel can be calculated. Notice that for BPSK signals, the power contained in the data channel arc calculated using the same equations as (20) and (23) for BPSK/Bi-phase and BPSK/NRZ, respectively.

For PCM/PSK/PM/Squarewave subcarrier, the data power containment, denoted as P1%, is given by

$$p1\% = \frac{8\sin^2(m)}{\pi^3}\sum_{k\geq 1}\frac{1}{(2k-1)^2}\int_{-\pi(M-n(2K-1))}^{\pi(M-n(2K-1))} [\sin(x)/x]^2\,dx \tag{32}$$

For PCM/PSK/PM/Sinewave subcarrier, the data power containment, denoted as P2%, is given by

$$P2\% = \sum_{h\ \text{even}}^{L} J_h^2(m)\,a_h(L) \tag{33}$$

For PCM/PM/Bi-phase, the data power containment, denoted as P3%, is given by

$$P3\% = \frac{2\sin^2(m)}{\pi} \int_{-M_3\pi/2}^{M_3\pi/2} [\sin^4(x)/x^2]\,dx \tag{34}$$

For PCM/PM/NRZ, the data power containment, denoted as P4%, is given by

$$P4\% = \frac{\sin^2(m)}{\pi} \int_{-M_4\pi}^{M_4\pi} [\sin^2(x)/x^2]\,dx \tag{35}$$

The power containment in the data channel for each modulation type is evaluated and the numerical results are presented in Figures, 11 and 12. The key results are also tabulated in Table 3, for the sake of comparison. This table shows the calculations of the data power efficiency for one-sided bandwidth of $2R_s$ and $4R_s$ for bo(h BPSK and PCM/PM signal with m = 1.3 rad for PCM/PM, and one-sided bandwidth of $20R_s$ for PCM/PSK/PM signals with m = 1.3 rad and n=3and9.

4,2 SYMBOL SNR DEGRADATION DUE TO 1S1

As mentioned earlier, the data power efficiency consists of two components, namely, data power containment and SSNR degradation due to 1S1. The issue concerning data power containment has been investigated in the proceeding section, Section 4.1. This section deals with SSNR degradation due to 1S1,

When the RF filter bandwidth is of the order of the main spectrum hump of the modulated carrier, the information-bearing pulses are spread out in time. Each pulse is overlaid with the tails of previous pulses and the precursors of the subsequent ones, and this so-called Intersymbol Interference (1S1) behaves like an additional random noise [7-12], This additional random noise can cause potential degradation to the receiver. In addition, excessive filtering of the pulse can also cause a loss of symbol energy during the symbol time. The effects of symbol energy's loss for specified bandwidths are already examined in Section 4,1 for the required bandwidth of $2R_s$

and $4R_s$. This section investigates the effects of 1S1 and the combined effects of 1S1 and imperfect carrier tracking on the symbol SNR degradation.

The effects of the ISI on the performance degradation of the PCM/PM receivers have been investigated in [7], where the SSNR degradation is evaluated for both PCM/PM/NRZ and PCM/PM/Bi-phase receivers for an ideal low-pass filter. Using results presented in [7-12], one can extend these to include PCM/PSK/PM and BPSK signal formats. To extend these results, it is necessary to give a brief summary on these key results. It has been shown in [7] that, for $BT \geq 1$ (where B denotes the required bandwidth), the average probability of error is given by:

$$P_e = \int_{\theta_e} P_e(\theta_e) P(\theta_e) d\theta_e \tag{36}$$

where $P_e(\theta_e)$ is the conditional probability of error and $P(\theta_e)$ is the probability density function (pdf) of the carrier tracking phase error θ_e. If the number of pulses, M, before and after the present pulse being detected is between 1 and 2, i.e., $1 \leq M \leq 2$, then direct computation of the conditional error probability $P_e(\theta_e)$ is feasible through the following equation [7, 12]

$$P_e(\theta_e) = (1/2)\ [\ (1/2^{2M}) \sum_{\substack{k=2^{2M} \\ \text{combinations}}} \operatorname{erfc}\{\sqrt{E_s/N_o}\,[1 + \Sigma' d_k \lambda_k] \cos\theta_e\} \tag{37}$$

Table 3: Data Power Efficiency and Unwanted Emission For Various Modulation Techniques Under Investigation

Modulation Type	Data Power Efficiency Without Filtering	Unwanted Spurious Emission		Remark
		Continuous Component	Discrete Component	
BPSK/NRZ	95 % (BW = 2R,)	570 (BW = 2R,)	0 %	
	97.5 % @W= 4R,)	2.5 % (BW = 4R,)		
BPSK/Bi-Phase	85.57 % (BW = 2R,)	14.43 % (BW = 2R,)	0 %	Recommend Filtering
	92.51 % (EIW = 4RJ	7.49 % (BW = 4RJ		
PCM/PM/NRZ (m =1.3 rad)	88.2 % (BW = 2R,)	4.64 % (BW = 2R,)	0 %	
	90.5 % (BW = 4R,)	2.3 % (BW = 4R,)		
PCM/PSK/Bi-Phase (m =1.3 rad)	79.45 % (BW = 2R,)	13.40 % (BW = 2R,)	070	Recommend Filtering
	85.89 % (BW = 4R')	6.95 % (BW = 4R,)		
PCM/PSK/PM - Squarewave (BW = 20R,) (m=1.3 rad)	74.84 % (n = 3)	18.01 % (n = 3)	0 %	Recommend filtering
	86.23 % (n = 9)	6.61 % (n = 9)		
PCM/PSK/PM - Sinewave (BW = 20R,) (m=1.3 rad)	54.16 % (n = 3)	0.69 % (n = 3)	6.71 (n = 3)	
	54.56 % (n =9)	0.28 % (n =9)	6.70 % (n =9)	

As an example, for M = 1, Eqn (37) becomes

$$
\begin{aligned}
P_e(\theta_e) = (1/2)\ [\ & (1/4)\,\mathrm{erfc}\{\sqrt{E_s/N_o}\,(1+\lambda_{-1}+\lambda_{+1})\cos\theta_e\} \\
& + (1/4)\,\mathrm{erfc}\{\sqrt{E_s/N_o}\,(1+\lambda_{-1}-\lambda_{+1})\cos\theta_e\} \\
& + (1/4)\,\mathrm{erfc}\{\sqrt{E_s/N_o}\,(1-\lambda_{-1}+\lambda_{+1})\cos\theta_e\} \\
& + (1/4)\,\mathrm{erfc}\{\sqrt{E_s/N_o}\,(1-\lambda_{-1}-\lambda_{+1})\cos\theta_e\}\ ]
\end{aligned}
\tag{38}
$$

where $d_k = \pm 1$ with $\Pr\{d_k = +1\} = \Pr\{d_k = -1\} = 1/2$, and

$$\lambda_k = \frac{\int_0^T 9(t)\ g(t+kT)\,dt}{\int_0^T |g(t)|^2\,dt} \tag{39}$$

where g(t) is defined as

$$g(t) = P(t) * h(t) \tag{40}$$

where * denotes the convolution,

For both PCM/PM/NRZ and PCM/PM/Bi-phase, the symbol energy is defined as

$$E_s = A2\sin2(mT)\int_0^T {}'g(t)|^2\,dt \tag{41}$$

Note that P(t) denotes the pulse shape of the data and h(t) denotes the impulse response of the equivalent low-pass filter of the RF bandpass filter, with the required bandwidth B.

When the loop signal-to-noise ratio is high, the Tikhonov pdf can be approximated by

$$P(\theta_e) \approx \exp(-\theta_e^2/2\sigma^2)/[2\pi\sigma^2]^{-1/2}, \quad -\infty < \theta_e < \infty \tag{42}$$

For perfect NRZ data stream and high-data-rate case (B_L/R_s cc 0.1, where B_L and R_s denote the one-sided carrier loop bandwidth and the symbol rate, respectively), the variance of the carrier tracking phase error is found to be

$$\sigma^2 = (1/pO) + (B_L/R_s)\tan^2(m_T) \tag{43}$$

and, for perfect Bi-ϕ data format, σ^2 becomes

$$0^2 = (l/pO) + (1/C)\tan^2(m,) \tag{44}$$

where ρ_o is the carrier loop SNR (under ideal operating conditions) which is found to be

$$\rho_o = \frac{(E_s/N_o)}{(B_L/R_s)\tan^2(m_T)} \tag{45}$$

and I/C is the interference-to-carrier ratio which is given by

$$\begin{aligned} I/C = {} & (1/2) + (9/16)\,(B_L/R_s)^{-1} \\ & (3/4)\,(B_L/R_s)^{-1}\exp\{-(2/3)(B_L/R_s)\}\,[\cos\{(2/3)(B_L/R_s)\} \\ & + 3\sin\{(2/3)(B_L/R_s)\}] \\ & + (3/16)\,(B_L/R_s)^{-1}\exp\{-(4/3)(B_L/R_s)\}\,[\cos\{(4/3)(B_L/R_s)\} \\ & + 3\sin\{(4/3)(B_L/R_s)\}] \end{aligned} \tag{46}$$

Reference [7] has shown that, for ideal low-pass filter and perfect data stream, the output of the filter for NRZ data format, denoted by $g_{NRZ}(t+kT)$, is given by

$$g_{NRZ}(t+kT_s) = \frac{1}{\pi}\,[si\{2\pi B(t+T(k+1/2))\} - si\{2\pi B(t+T(k-1/2))\}] \tag{47}$$

For Bi-ϕ data format one gets

$$\begin{aligned} g_{Bi\text{-}\phi}(t+kT_s) = \frac{1}{\pi}\, & [si\{2\pi B(t+T(k+1/2))\} + si\{2\pi B(t+T(k-1/2))\} \\ & - 2si(2\pi B(t+kT)\,] \end{aligned} \tag{48}$$

where B is the one-sided bandwidth of the low-pass filter and it can be set equal to the required bandwidth, and

$$si(x) = \int_0^x [\sin(u)/u]\,du \tag{49}$$

For PCM/PSK/PM with $n \geq 3$, the variance of the carrier tracking phase error becomes

$$\sigma^2 = (1/\rho_o) \tag{50}$$

For PCM/PSK/PM-squarewave, the carrier loop SNR is identical to PCM/PM (see Eqn (45)). However, for PCM/PSK/PM-sinewave, the carrier loop SNR becomes

$$\rho_o = \frac{J_0^2(m_T)\,(E_s/N_o)}{2\,(B_L/R_s)\,J_1^2(m_T)} \tag{51}$$

where E_s is given by

$$E_s = 2A^2 J_1^2(m_T) \int_0^T |g(t)|^2\, dt \tag{52}$$

For BPSK, the loop SNR, ρ, of a Costas is given by [6]

$$\rho = \frac{A^2}{N_0 B_L} S_L \tag{53}$$

where S_L is the squaring loss which is given by the simple relation

$$S_L = \frac{K_1^2}{K_1 K_2 + K_L K} \tag{54}$$

where

$$K_1 = \int_{-\infty}^{\infty} S_d(f)\, |G(j2\pi f)|^2\, df \tag{55}$$

$$K_2 = \frac{\int_{-\infty}^{\infty} S_d(f)\, |G(j2\pi f)|^4\, df}{\int_{-\infty}^{\infty} S_d(f)\, |G(j2\pi f)|^2\, df} \tag{56}$$

$$K_L = \frac{\int_{-\infty}^{\infty} |G(j2\pi f)|^4\, df}{\int_{-\infty}^{\infty} |G(j2\pi f)|^2\, df} \tag{57}$$

$$K = \frac{BT}{E_s/N_0} \tag{58}$$

where $S_d(f)$ denotes the power spectral density of the data modulation d(t), $G(j2\pi f)$ is the transfer function of the low-pass arm filter. Again, the parameter B in Eqn (47) is the single-sided noise bandwidth of the low-pass arm filter of the Costas loop, i.e.,

$$B = \int_{-\infty}^{\infty} |G(j2\pi f)|^2 \, df \tag{59}$$

Note that B can have the same value as the required bandwidth.

For NRZ and Bi-phase data modulation, the power spectral densities are identical to Eqns (12) and (19), respectively. Furthermore, for n-pole Butterworth filter, the transfer function of the arm filter is

$$|G(j2\pi f)|^2 = [1 + (f/f_c)^{2n}]^{-1} \tag{60}$$

where f_c is the 3-dB bandwidth which is related to the single-sided noise bandwidth B of the arm filter:

$$f_c = (2Bn/\pi)\sin(\pi/2n) \tag{61}$$

For ideal arm filter, i.e. rectangular frequency response, the squaring loss S_L becomes

$$S_L = \frac{K_3^2}{K_3 + [BT/(E_s/N_0)]} \tag{62}$$

where

$$K_3 = \frac{2}{\pi}\left[Si(2\pi BT) - \frac{\sin^2(\pi BT)}{\pi BT}\right] \tag{63}$$

and Si(x) is defined in Eqn (49).

In the absence of ISI, the average BER, PE_O, for an uncoded channel is well-known to be given by:

$$PE_O = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{(E_s/N_0)_0}\right) \tag{64}$$

where $(E_s/N_0)_0$ is the required symbol SNR to achieve a desired SER, PE_O, for unlimited bandwidth case.

In the presence of bandlimiting channel, the average SER, PE_1, for an uncoded channel can be calculated from Eqn (36). Let $(E_s/N_0)_1$ be the required symbol SNR to achieve a desired SER, PE_1, for bandlimiting case, Thus, if we fix the SER, i.e.,

$PE_O = PE_1 = SER_O$ (a desired value)

then the SSNR degradation in dB for this specified SER_O is defined as:

$$A\ (dB) = (E_s/N_0)_O - (E_s/N_0)_1 \tag{65}$$

The value of $(E_s/N_0)_0$ can be computed by using Eqn (64). To compute $(E_s/N_0)_1$ for PCM/PM/NRZ, we substitute Eqns (37) and (42) into Eqn (36) with the carrier tracking jitter (o*) given by Eqn (43) and performing numerical integration on the digital computer. Having $(E_s/N_0)_0$ and $(E_s/N_0)_1$, one can calculate the SSNR degradation in dB using Eqn (65). The calculated SSNR degradation in dB for various modulation types are presented in Table 2. Table 4 shows the results for m = 1.3 rad, $(2B_L/R_s) = 0.001$ at SER = 10-5. Note that the carrier loop SNR (p_o) is fixed in the calculation of the SSNR degradation for all cases.

The SSNR degradation due to 1S1 alone can be computed form Eqn (36) by letting the loop SNR approaches infinity. Using the same input parameters as in Table 4, the results of the calculations arc shown in Table 5. Comparing the results presented in Tables 4 and 5, it is clear that, for BT $\geq$ 5, the SSNR degradations arc about the same for both cases, i.e., perfect and imperfect carrier tracking.

Table 4. Symbol SNR Degradation in dB Due to 1S1 and Imperfect Carrier Tracking for Various Modulation Schemes at SER = 10-5

Modulation Type	Symbol SNR Degradation (dB)		
	BT=I	BT=2	BT=5
PCM/PSK/PM-Squarewave ($m = 1.3$ rad, $2B_L/R_s = 0.001$)	0.85	0.17	0.01
PCM/PSK/PM-Sinewave ($m = 1.3$ rad, $2B_L/R_s = 0.001$)	0.85	0.18	0,04
PCM/PM/NRZ ($m = 1.3$ rad, $2B_L/R_s = 0.001$)	0.95	0.21	0.01
PCM/PM/Bi-Phase ($m = 1.3$ rad, $2B_L/R_s = 0.001$)	10.89	0.34	0.20
BPSK/NRZ ($2B_L/R_s = 0.001$)	0.74	0.17	0.04
13 PSK/Bi-Phase ($2B_L/R_s = 0.001$)	10.85	0.29	0.15

Table 5. Symbol SNR Degradation in dB Duc to 1S1 for Various Modulation Schemes at SER = 10^{-5}

Modulation Type	Symbol SNR Degradation (dB)		
	BT = 1	BT=2	BT=5
PCM/PSK/PM-Squarewave ($m = 1.3$ rad, $2B_L/R_s = 0,001$)	0.85	0.17	0.01
PCM/PSK/PM-Sinewave ($m = 1.3$ rad, $2B_L/R_s = 0.001$)	0.85	0.17	0.01
PCM/PM/NRZ ($m = 1.3$ rad, $2B_L/R_s = 0.001$)	0.85	0.17	0.01
PCM/PM/Bi-Phase ($m = 1.3$ rad, $2B_L/R_s = 0.001$)	10.)	0.18	0.09
BPSK/NRZ ($2B_L/R_s = 0.001$)	0.85	0.17	0,01
BPSK/Bi-Phase ($2B_L/R_s = 0.001$)	10.1	0.18	0.09

5. OPTIMUM REQUIRED BANDWIDTH IN THE PRESENCE OF NOISE

Since it is interested to know at what point the noise power in a specified "required bandwidth" would have the same power as the signal, and that one may consider this bandwidth as the "optimum required bandwidth". This is because when the required bandwidth exceeds that of the optimum required bandwidth, then the noise power will exceed that of the signal power and hence degrades the system performance. Therefore, the term "optimum required bandwidth" considered in this section is defined as the bandwidth that is required to achieve the same amount of power contained in the signal as well as in the noise.

This section focuses on the calculation of the optimum required bandwidth in the presence of the white Gaussian noise for BPSK signals only. Extension of the method presented here to other modulation types is straight forward. Let P, be the total transmitted power, and P_s be the signal power, The signal power-to-the total ransmitted power can be defined as follow

$$\frac{P_s}{P_t} = \int_{-BW}^{BW} S(f)\, df \qquad (51)$$

where BW is the required bandwidth and S(f) is the PSD of the transmitted signal. As an example, for BPSK/Bi-phase and BPSK/NRZ, the PSD's are given by Eqns (19) and (22), respectively.

Similarly, the noise power-to-the tots' transmitted power is given by

$$\frac{P_n}{P_t} = \frac{2N_0 BW}{P_t} \qquad (52)$$

where NO is one-sided spectral density of the noise. Note tha Eqn (52) can be rewritten in terms of the normalized bandwidth M, i.e., M = BW/R_s, and the Symbol Signal-to-Noise Ratio (SSNR), SSNR = E_s/N_0 = P,T/NO, as follow

$$\frac{P_n}{P_t} = \frac{2M}{SSNR} \tag{53}$$

Dividing Eqn (51) by (53) we obtain

$$\frac{P_s}{P_n} = \frac{SSNR}{2M} \int_{-BW}^{BW} S(f)\, df \tag{54}$$

where the optimum bandwidth is selected in such a way that the ratio in Eqn (54) is unity. The plots of Eqns (51), (53) and (54) are shown in Figures 13-16. Figures 13 and 14 show the results for BPSK/NRZ, and Figures 15 and 16 are for BPS K/Bi-phase. These figures plot the percentage of power containment as a function of the normalized bandwidth with SSNR as parameter. These figures show that for SSNR = 10 dB, the optimum bandwidths for both BPSK/NRZ and BPSK/Bi-phase are about $5R_s$. Furthermore, maximum P_s/P_n occurs at $BW = R_s$ for BPSK/NRZ, and at $BW = 2R_s$ for BPSK/Bi-phase.

6. DISCUSSIONS

It is clearly shown in Figures 3 and 4 that as the desired signal power containment increases above 90 %, the required bandwidth for PCM/PSK/PM-squarewave increases much faster than that of PCM/PSK/PM-sinewave. As mentioned earlier, for 99 % power containment, the one-sided bandwidths for PCM/PSK/PM-squarewave and PCM/PSK/PM-sinewave arc about $328R_s$ and 27 R_s, respectively, for m = 1.2 rad and n = 9. Hence, for PCM/PSK/PM-squarewave signal with high data rate, it is suggested that the required bandwidth should be calculated before the frequency assignment.

Figures 5 and 6 shows that for signal power containment below 95 %, the required bandwidth for PCM/PM/Bi-phase is approximately twice that of PCM/PM/NRZ. But when the signal power containment exceeds 95 %, the required bandwidth for PCM/PM/Bi-phase grows exponentially as compare to PCM/PM/NRZ. The same is true for BPSK/Bi-phase and

BPSK/NRZ. This is demonstrated in Figure 7. Based on the numerical results shown in Figures 3-7, BPSK/NRZ and PCM/PM/NRZ signals require the least bandwidth and PCM/PSK/PM-squarewave requires the most bandwidth.

Figures 13-16 illustrate the effects of the noise on the optimum required bandwidth for BPSK/NRZ and BPSK/Bi-ϕ. The numerical results show that the optimum required bandwidth in the presence of noise for BPSK, regardless of the data format, is about $4R_s$ (two-sided bandwidth).

It is also shown in Table 3 that for a fixed one-sided bandwidth of $2R_s$, BPSK/NRZ and PCM/PM/NRZ have the most power in the data channel as compare to the other modulation schemes. Concerning the unwanted spurious emission, the use of squarewave subcarrier and Bi-phase data format produce more out-of-band power than the sinewave subcarrier and NRZ data format,

Tables 4 and 5 exemplify the effects of 1S1 on the symbol SNR degradations when the required bandwidths are at R_s (BT = 1), $2R_s$ (BT = 2) and $5R_s$ (BT = 5). The results show that PCM/PM/NRZ provides relatively good performance as compared with the others. For instance, for BT =2, the symbol SNR degradations (caused by 1S1 and imperfect carrier tracking) associated with PCM/PSK/PM-Square, PCM/PSK/PM-Sine, PCM/PM/NRZ, PCMLPM/Bi-phase, BPSK/NRZ and BPSK/Bi-phase are about 0.15, 0.18, 0.21, 0.34, 0.17 and 0,29 dB, respectively.

7. CONCLUSION

Because of the difficulties with the ITU definitions for Occupied Bandwidth and Necessary Bandwidth, a new definition for bandwidth has been proposed. Because spectrum shaping is intrinsic in the concept of the proposed required bandwidth, the definition should specify the percentage of power containment (acceptable loss). A suggested level of 95 % (0.2 dB) is recommended for the required bandwidth.

In order to achieve the same data power containment, the use of residual carrier modulation technique will require more bandwidth than the suppressed carrier modulation technique. In particular, BPSK/NRZ provides the best compromise between data power efficiency and unwanted emission as compared to BPSK/Bi-phase, PCM/PM/NRZ, PCM/PM/Bi-phase, PCM/PSK/PM-squarewave and PCM/PSK/PM-sinewave. However, PCM/PM/NRZ also provides compatible performance, in terms of high power containment and low level of unwanted emission, as compared to 13 PSK/NRZ. It is clearly shown in this paper that the use of subcarrier requires much larger bandwidth than that of the systems without using subcarrier. Because frequency spectrum is a scarce resource, it is recommended that the use of subcarrier should not be employed at high data rate, and that PCM/PM/NRZ modulation scheme should be used in place of PCM/PSK/PM.

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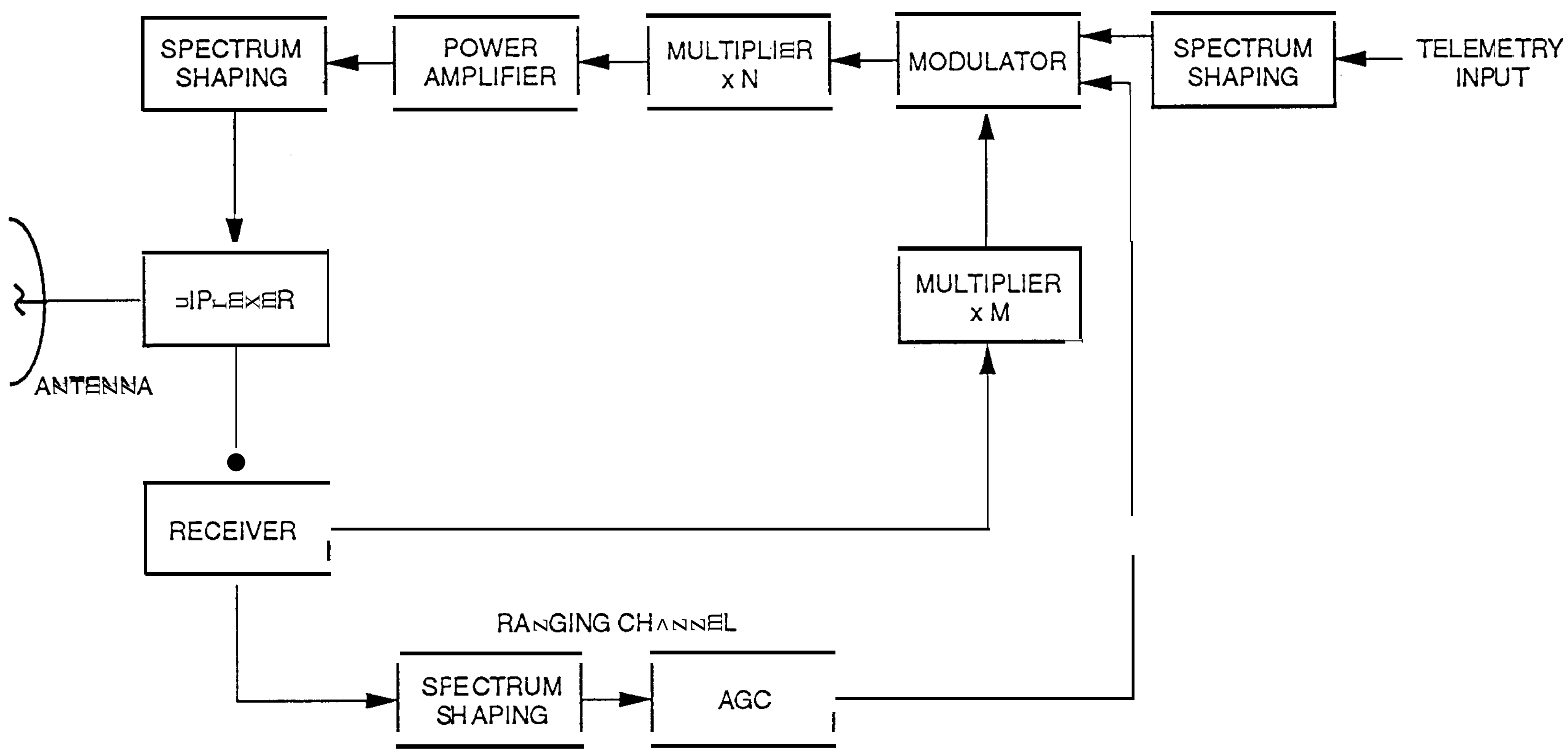

Figure 1. Simplified B Diagram of Spacecraft Radio Frequency Subsystem

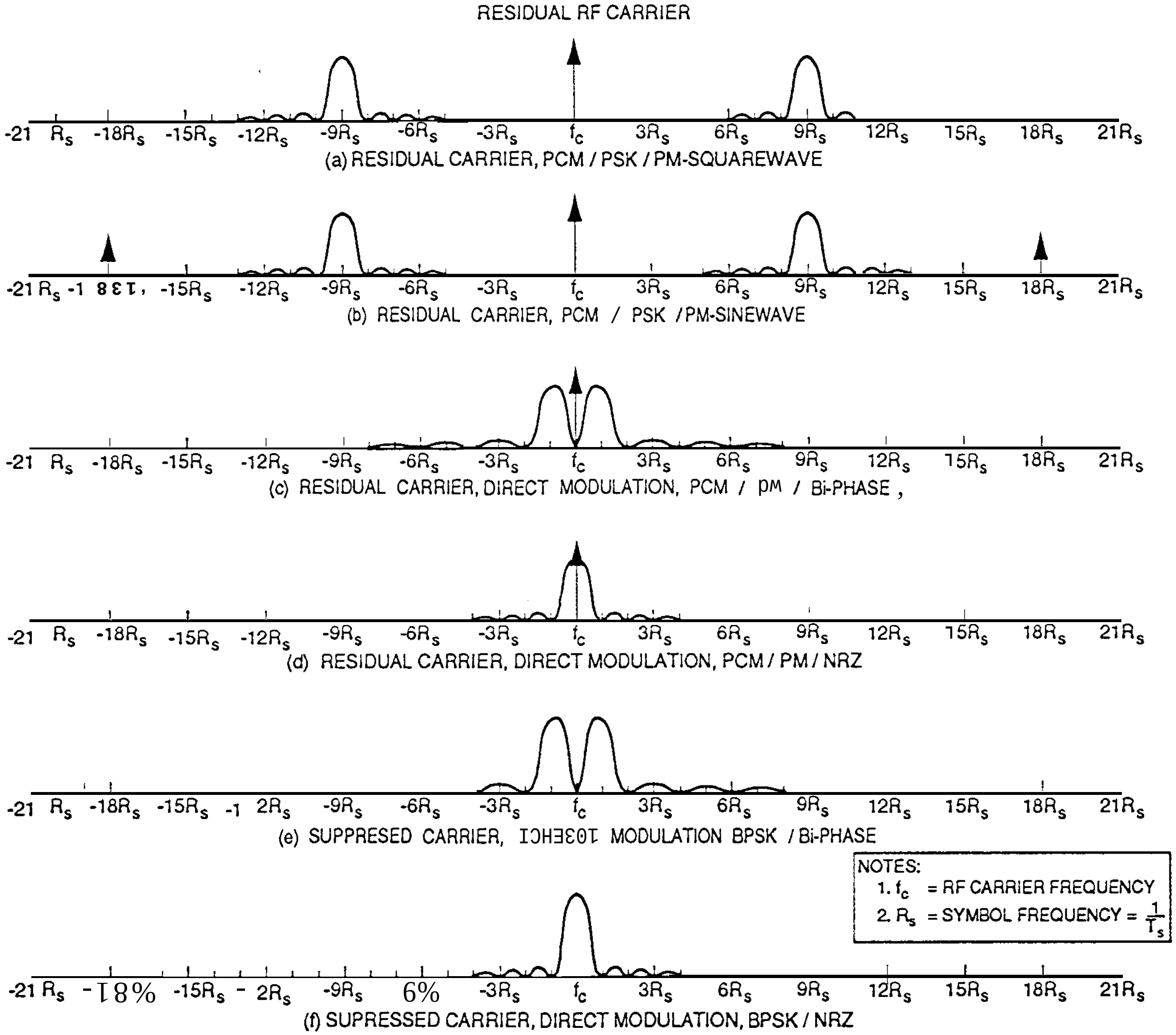

Figure 2. Spectra of Various Modulation Methods

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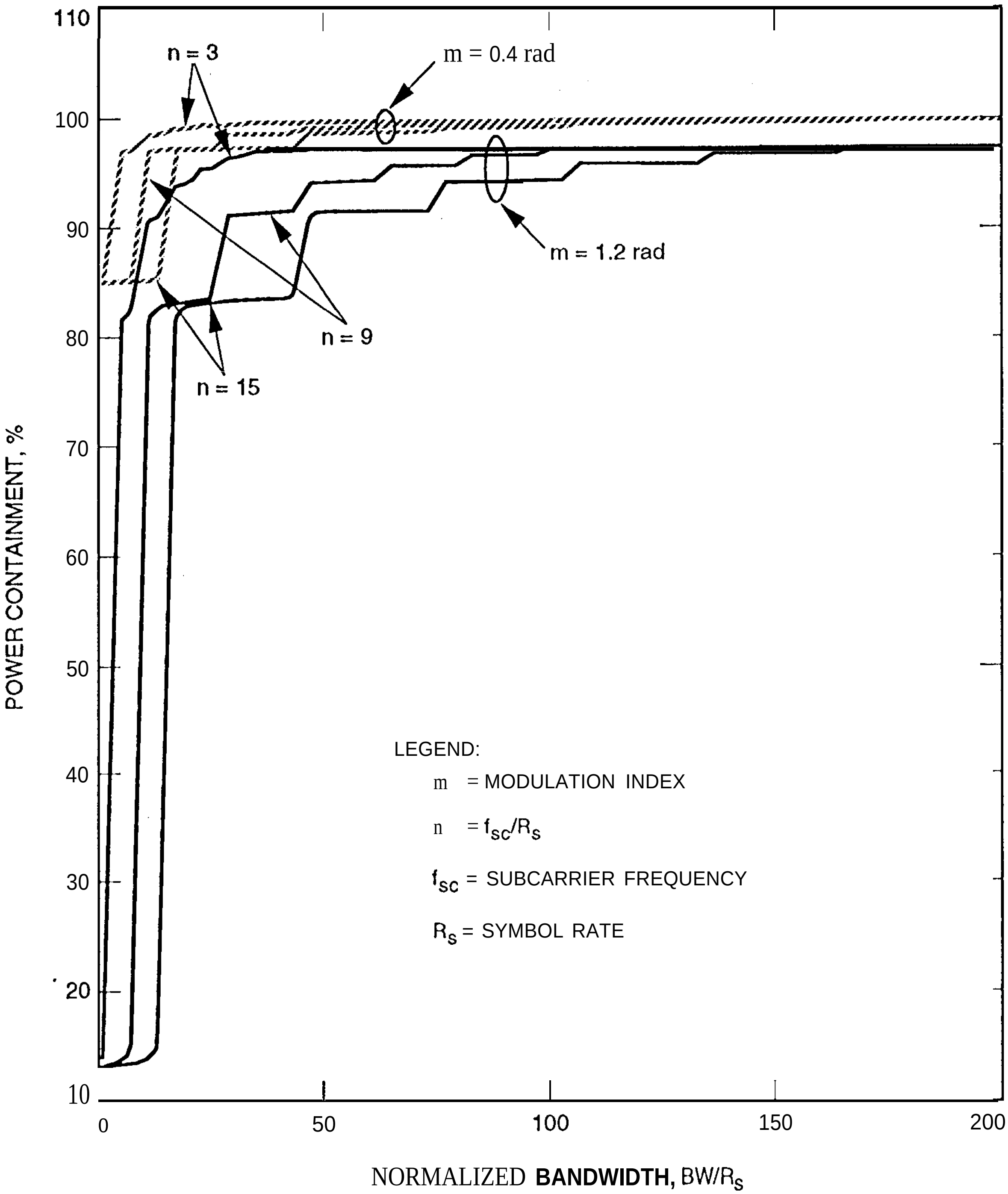

Figure 3. Bandwidth Needed for PCM/PStVPM-Squarewave

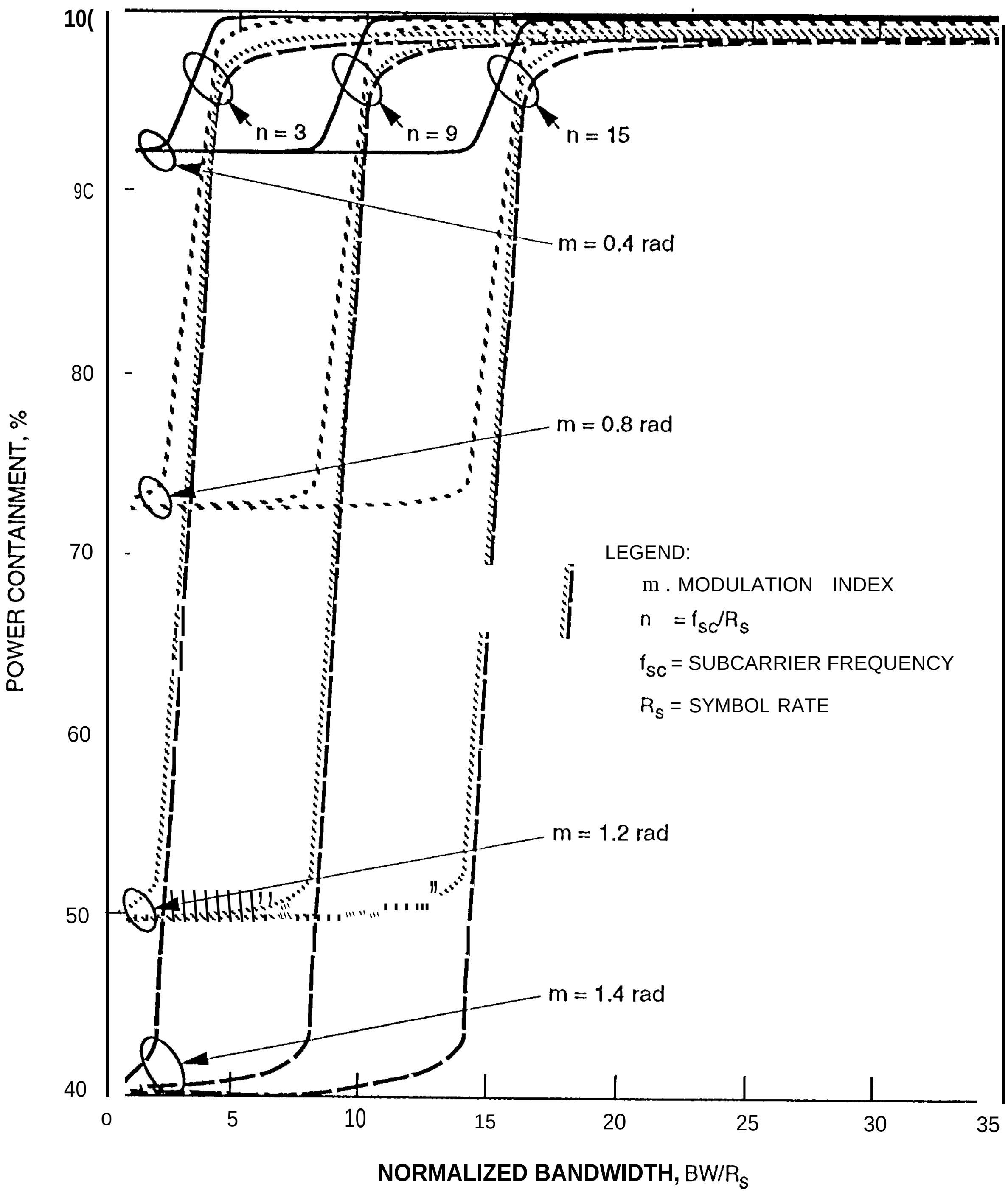

Figure 4. Bandwidth Needed for PCM/PStVPM-Sinewave

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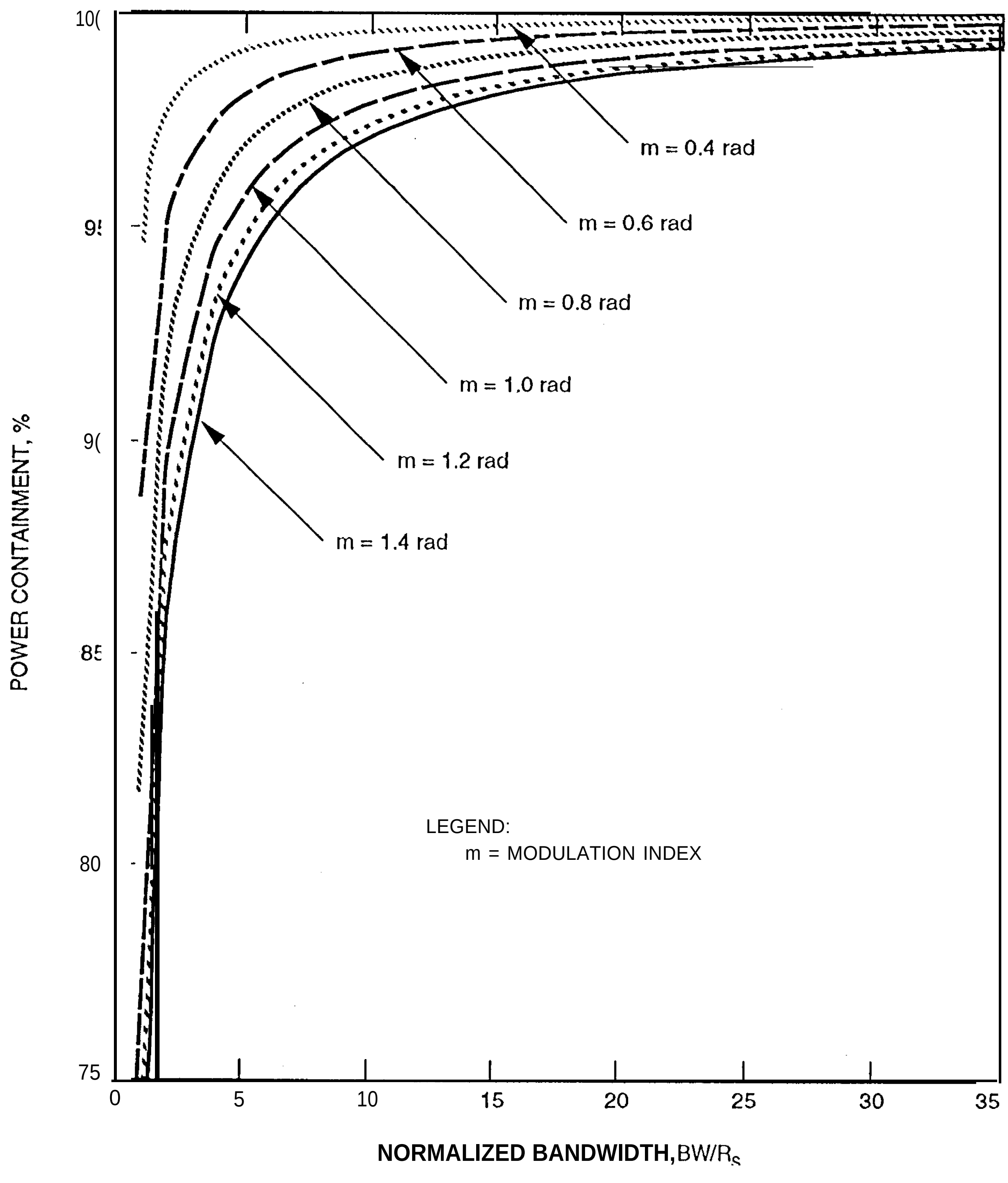

Figure 5. Bandwidth Needed **for** PCM/PM/Bi-Phase

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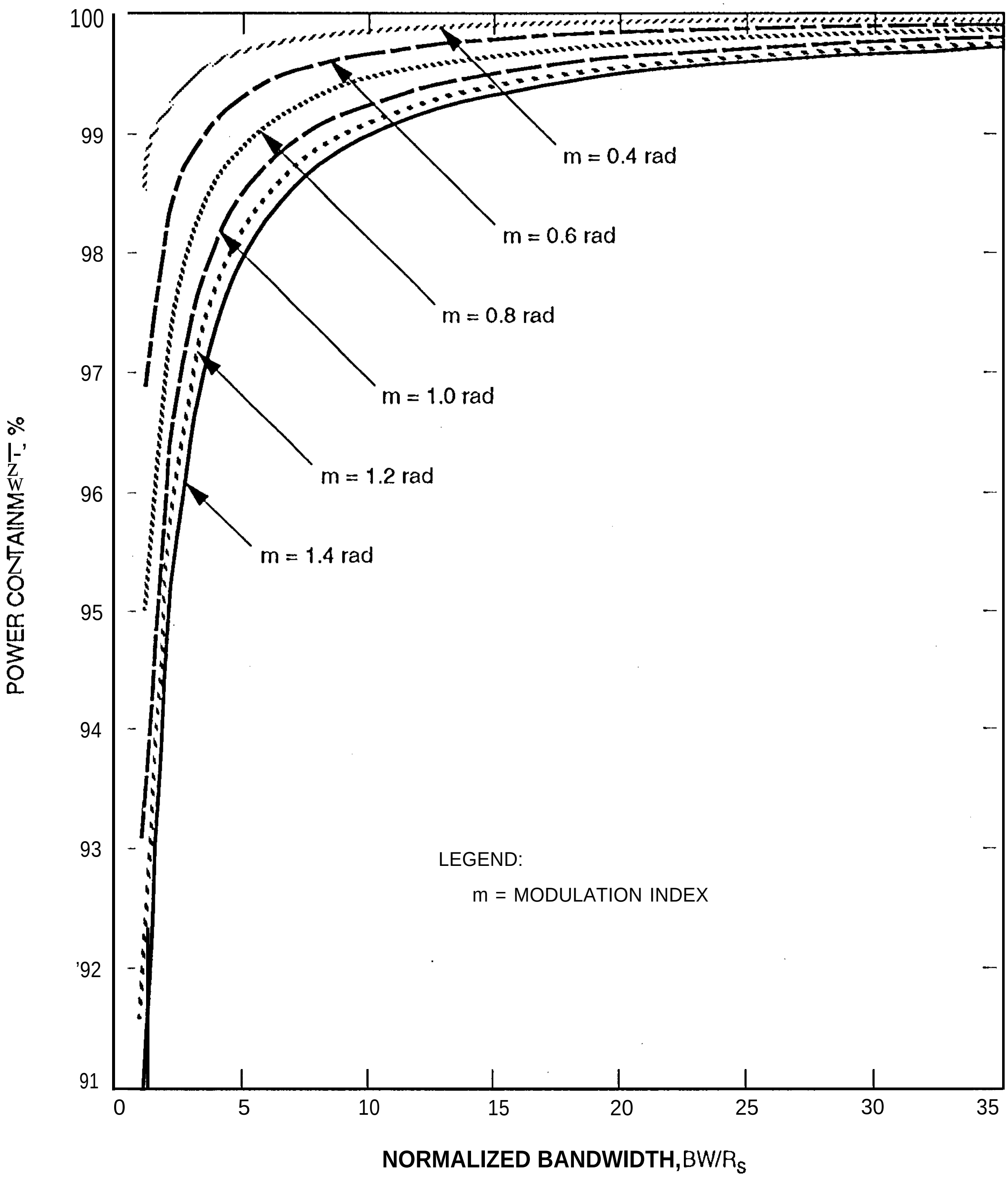

Figure 6. Bandwidth **Needed for PCM/PM/NRZ**

6485-35576p

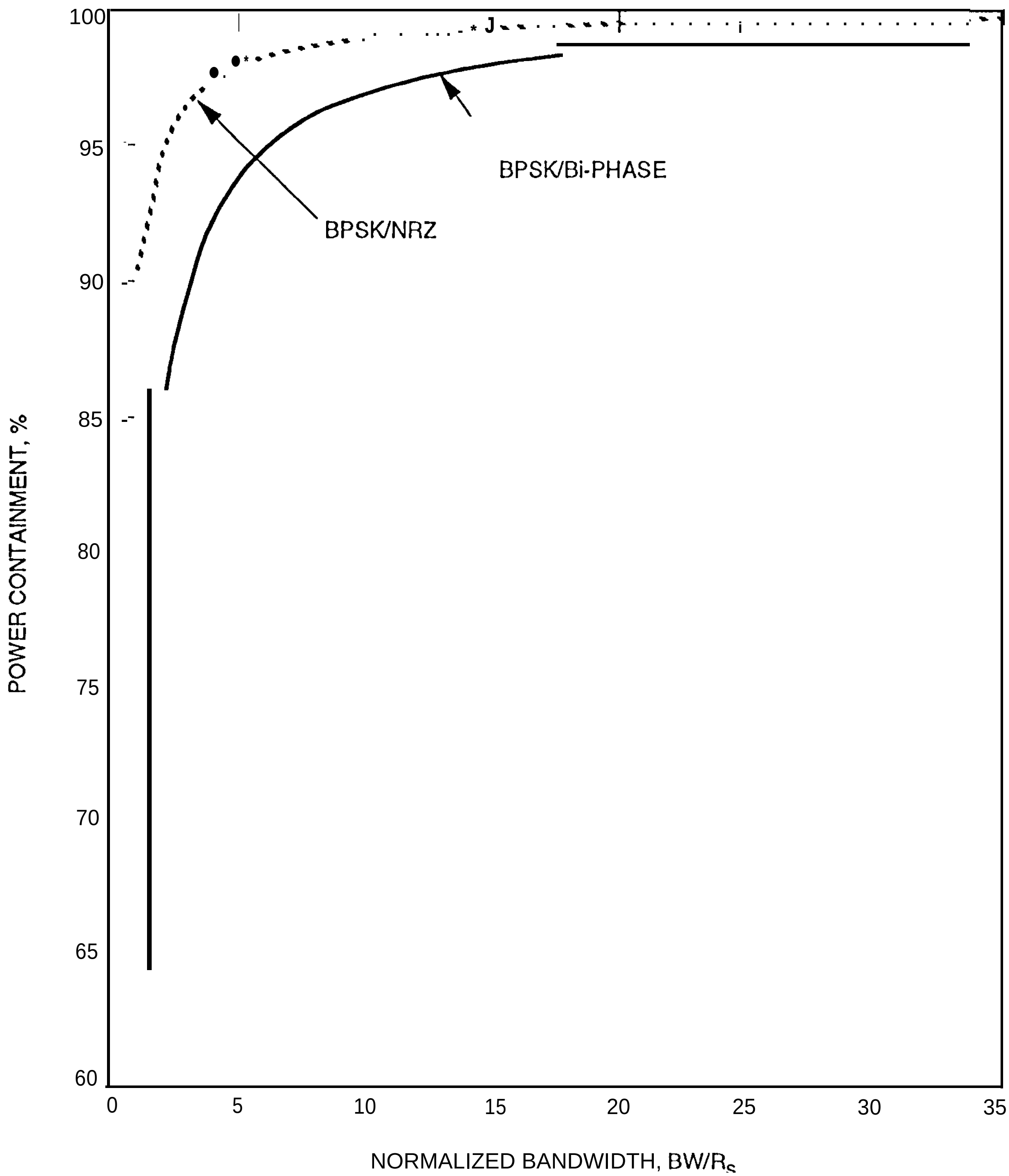

Figure 7. Bandwidth Needed for BPSK Signals

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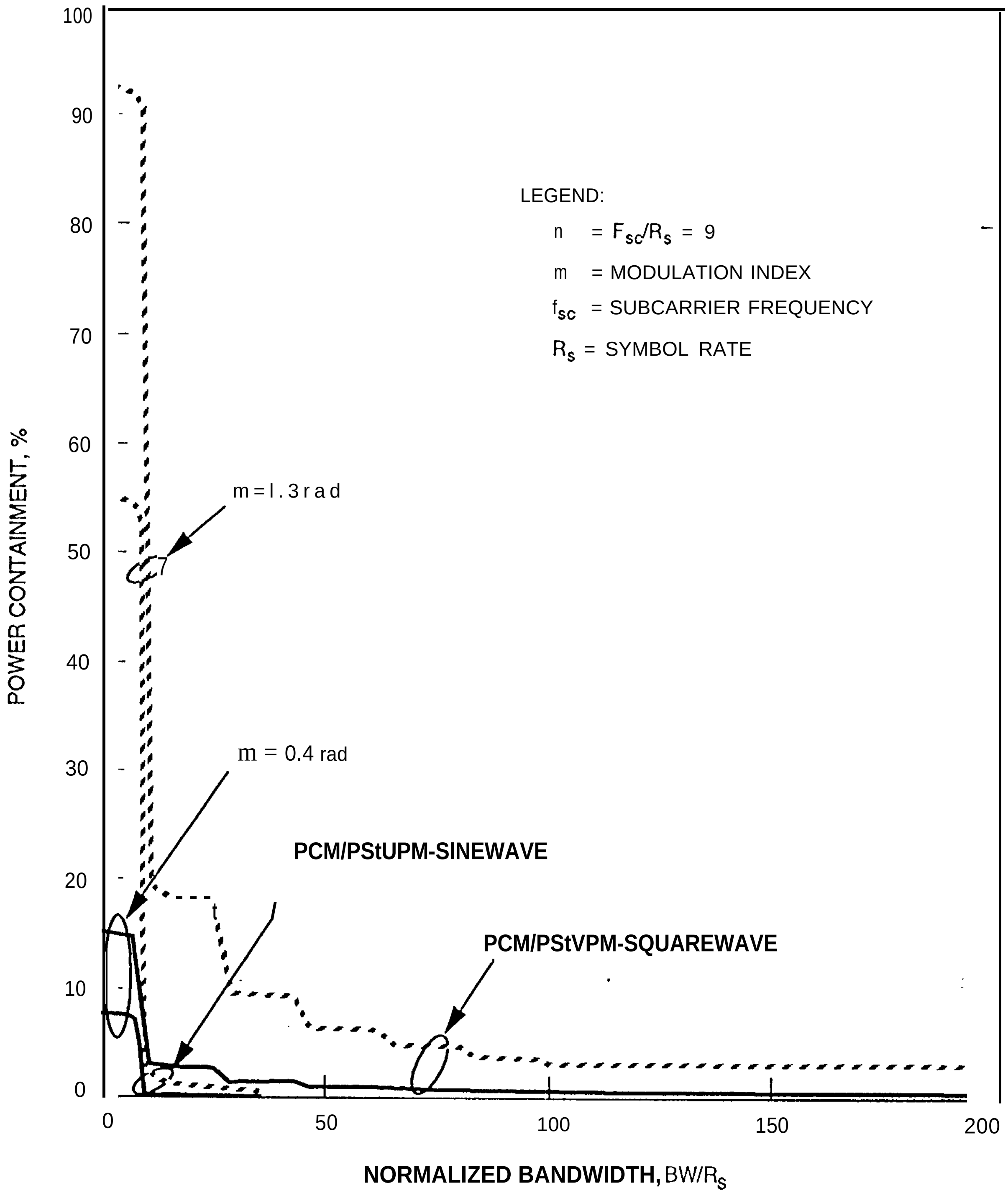

Figure 8. Unwanted Emission for PCM/PSK/PM Signals

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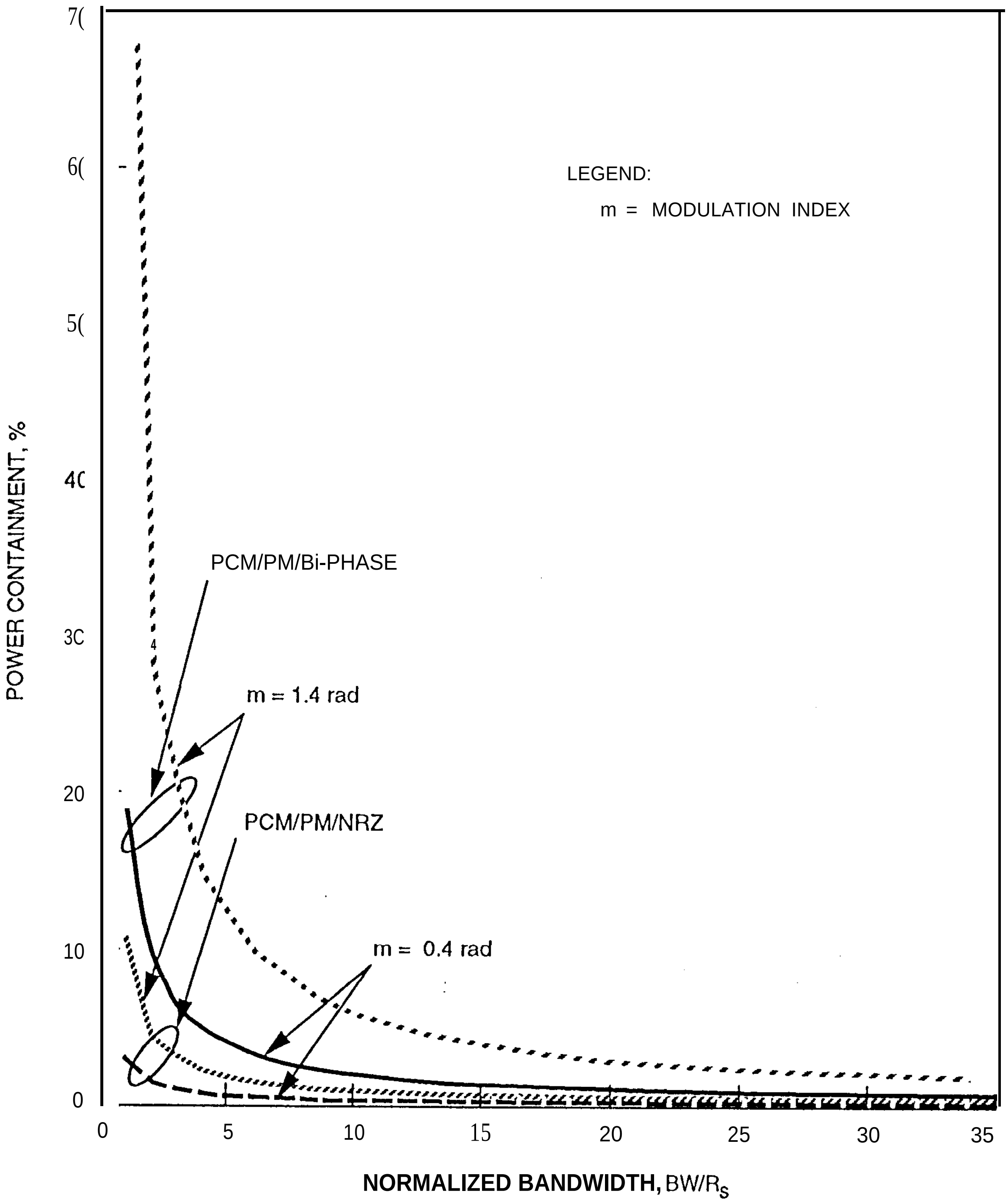

Figure 9. Unwanted Emission for PCM/PM Signals

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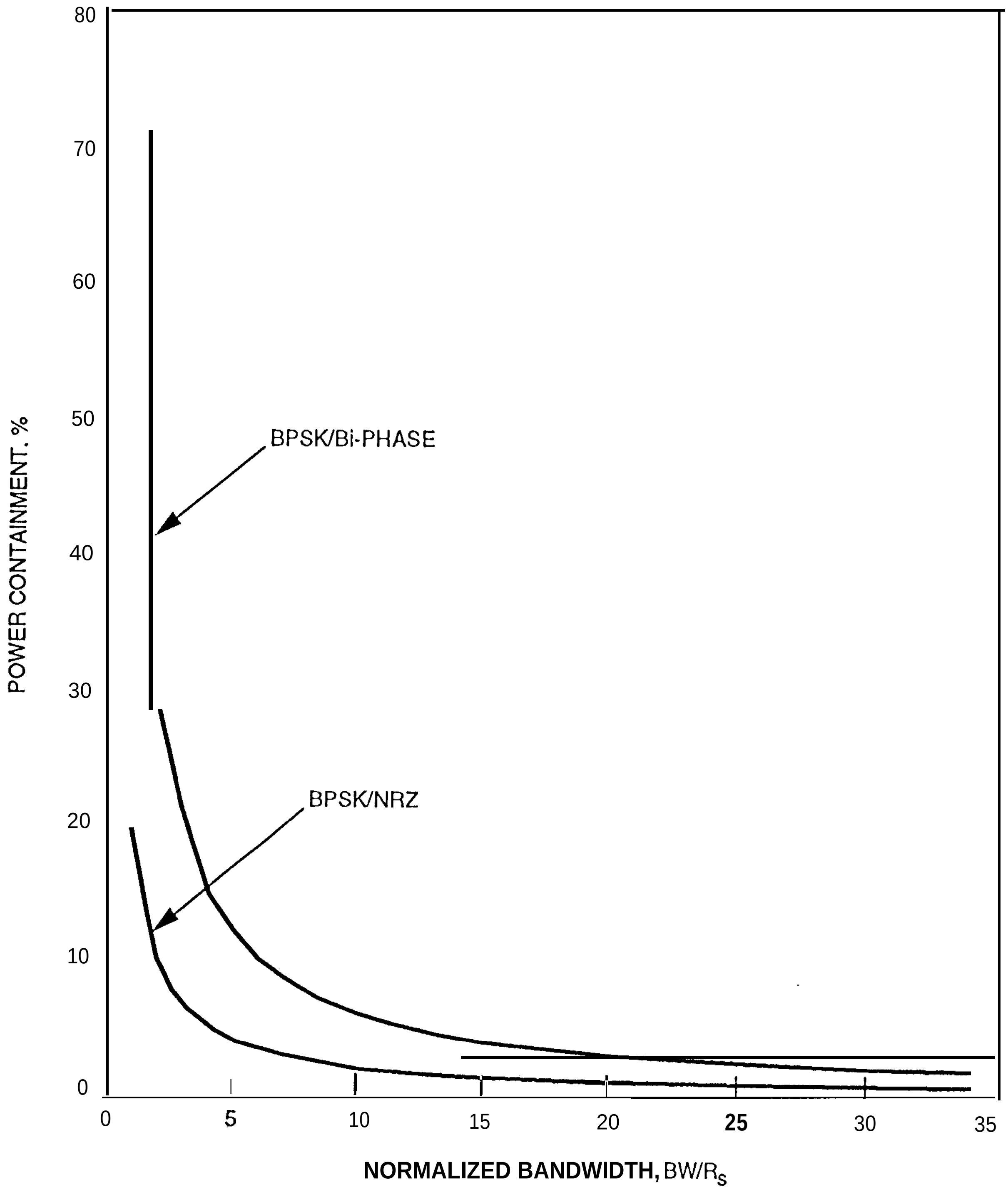

Figure 10. Unwanted Emission for BPSK Signals

6485-35584p

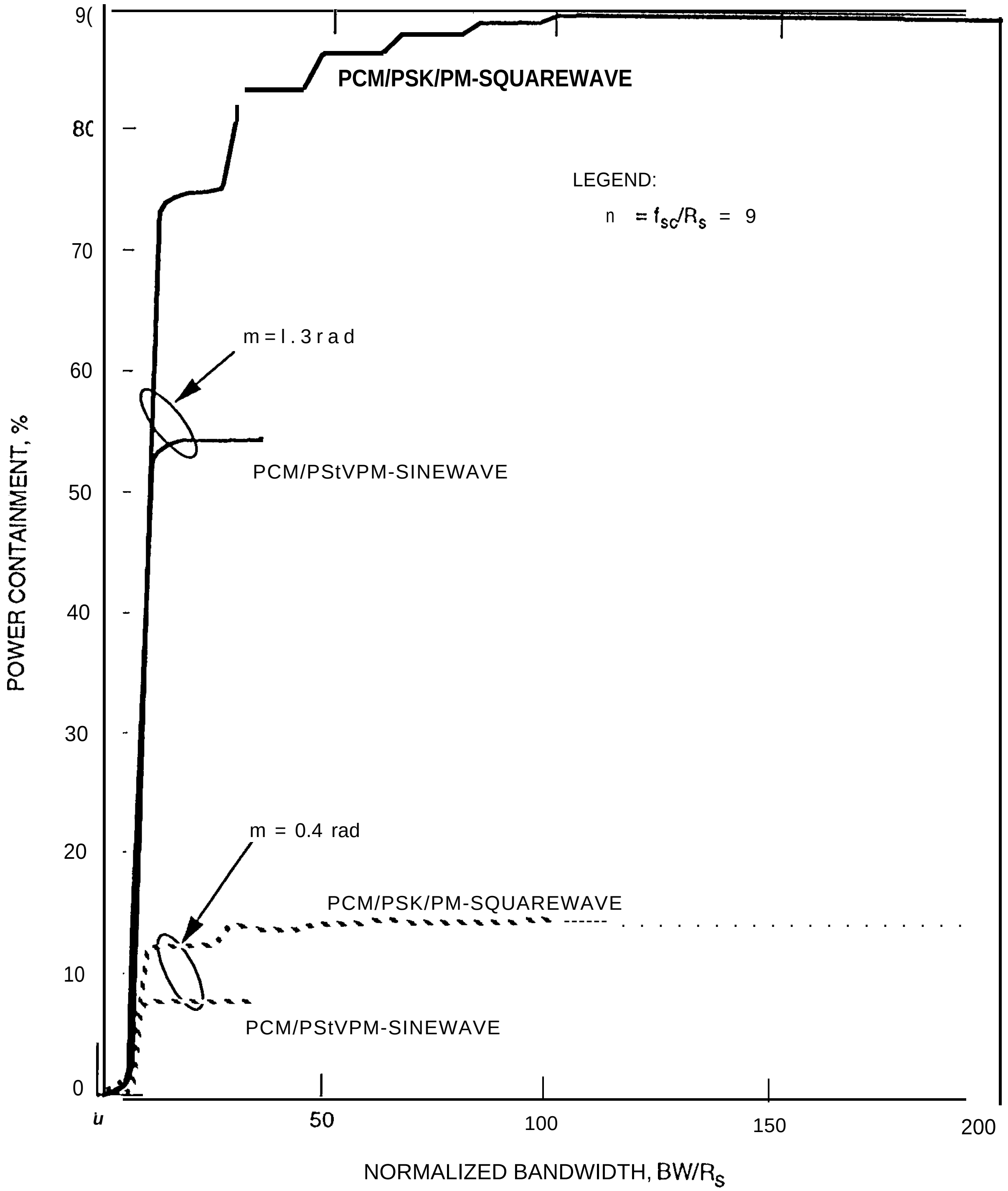

Figure 11, Data Power Containment for PCM/PSK/PM

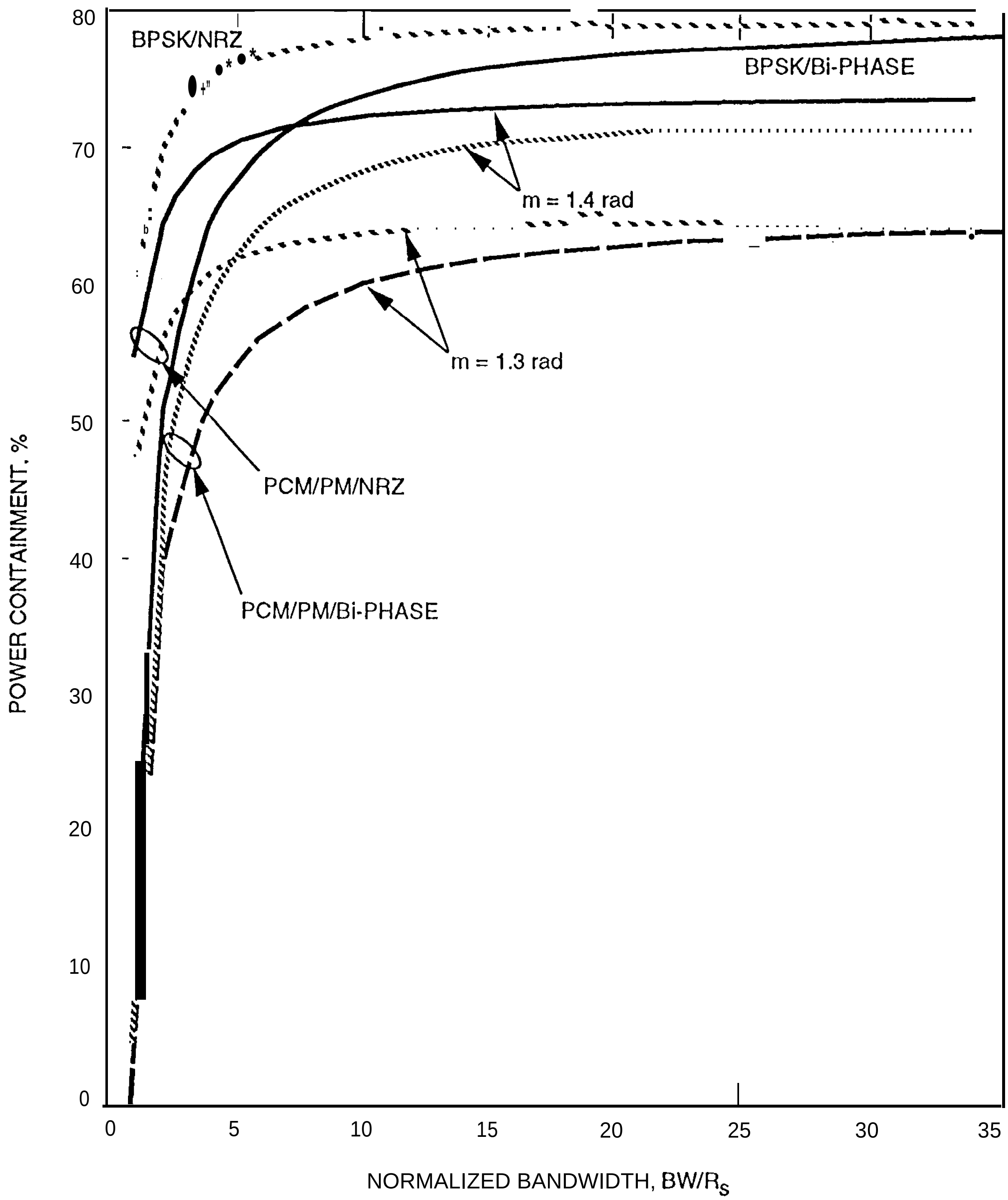

Figure 12. Data Power Containment for BPSK and PCM/PM

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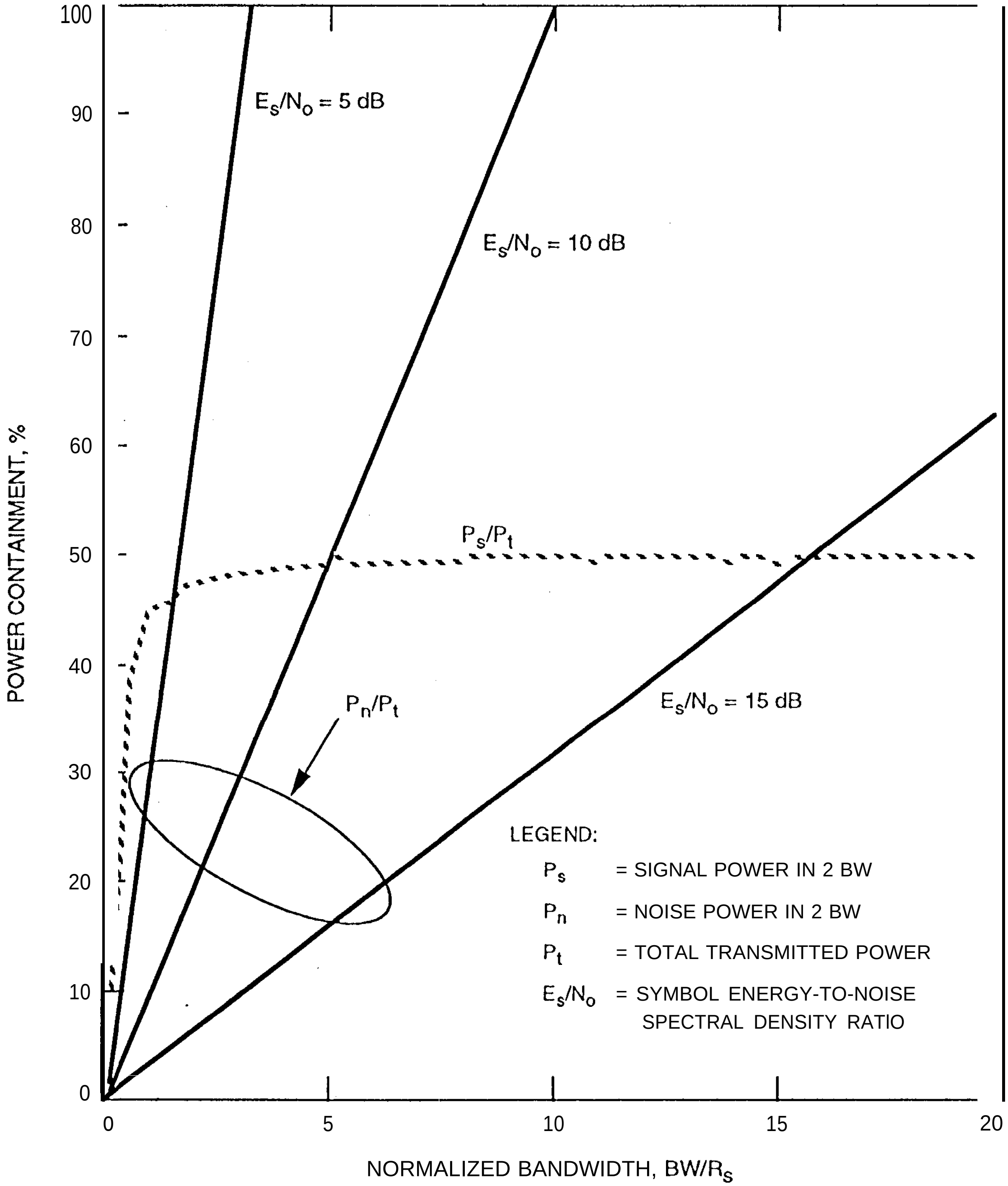

Figure 13 BPSK/NRZ in the Presence of Noise

6485-35578p

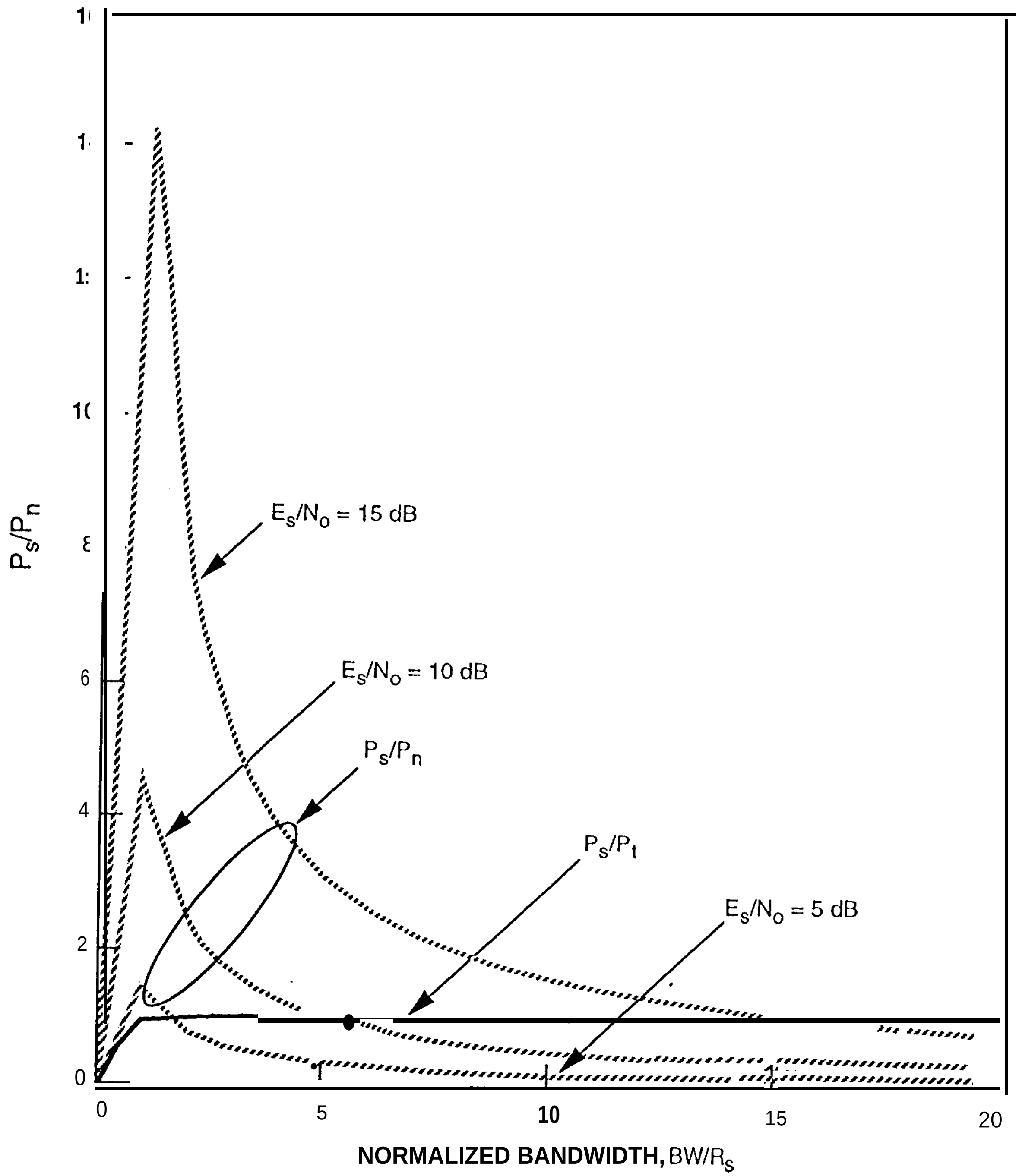

Figure 14 BPSK/NRZ in the Presence of Noise

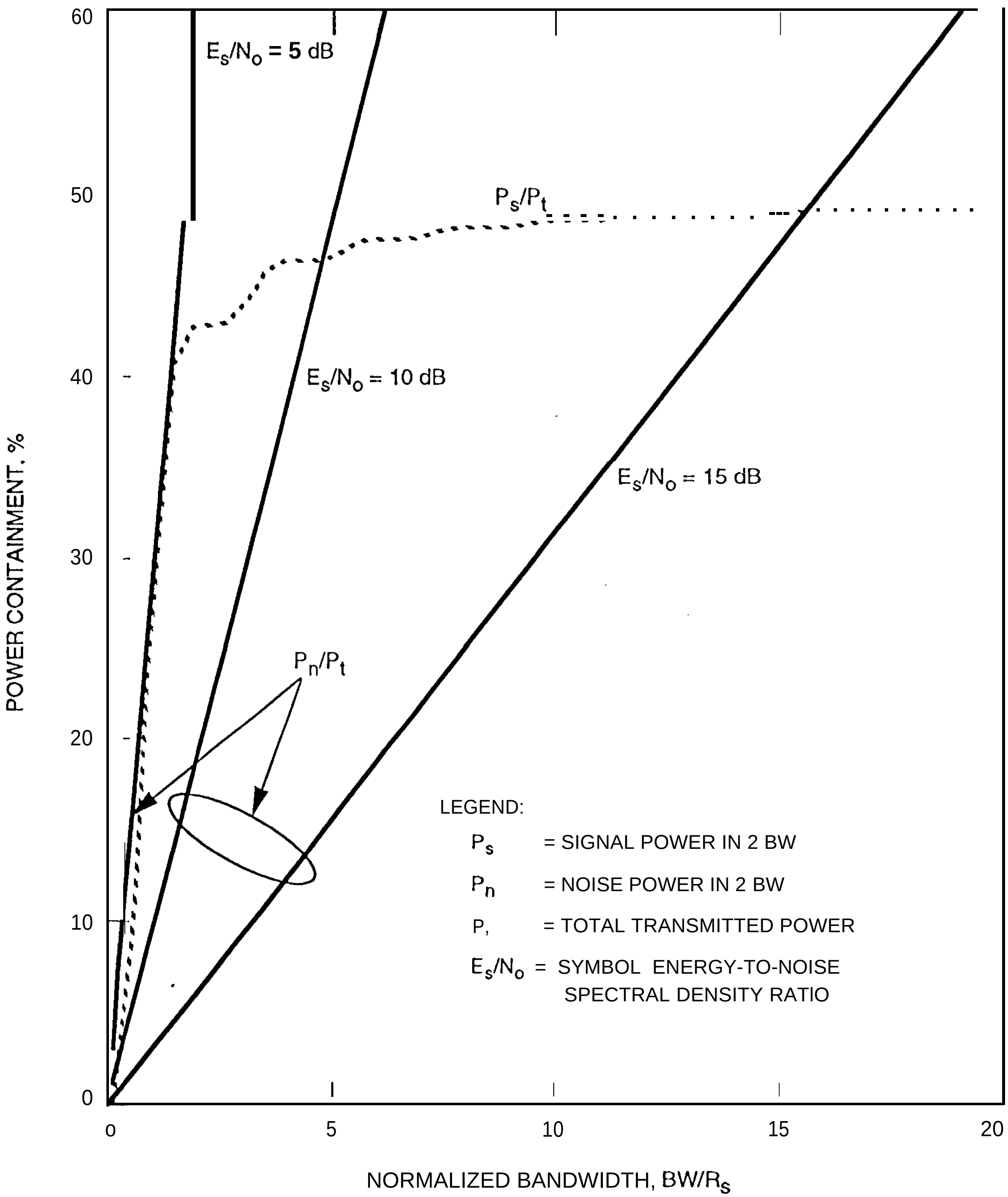

Figure 15. BPSK/Bi-Phase **in the Presence of** Noise

6485-35580p

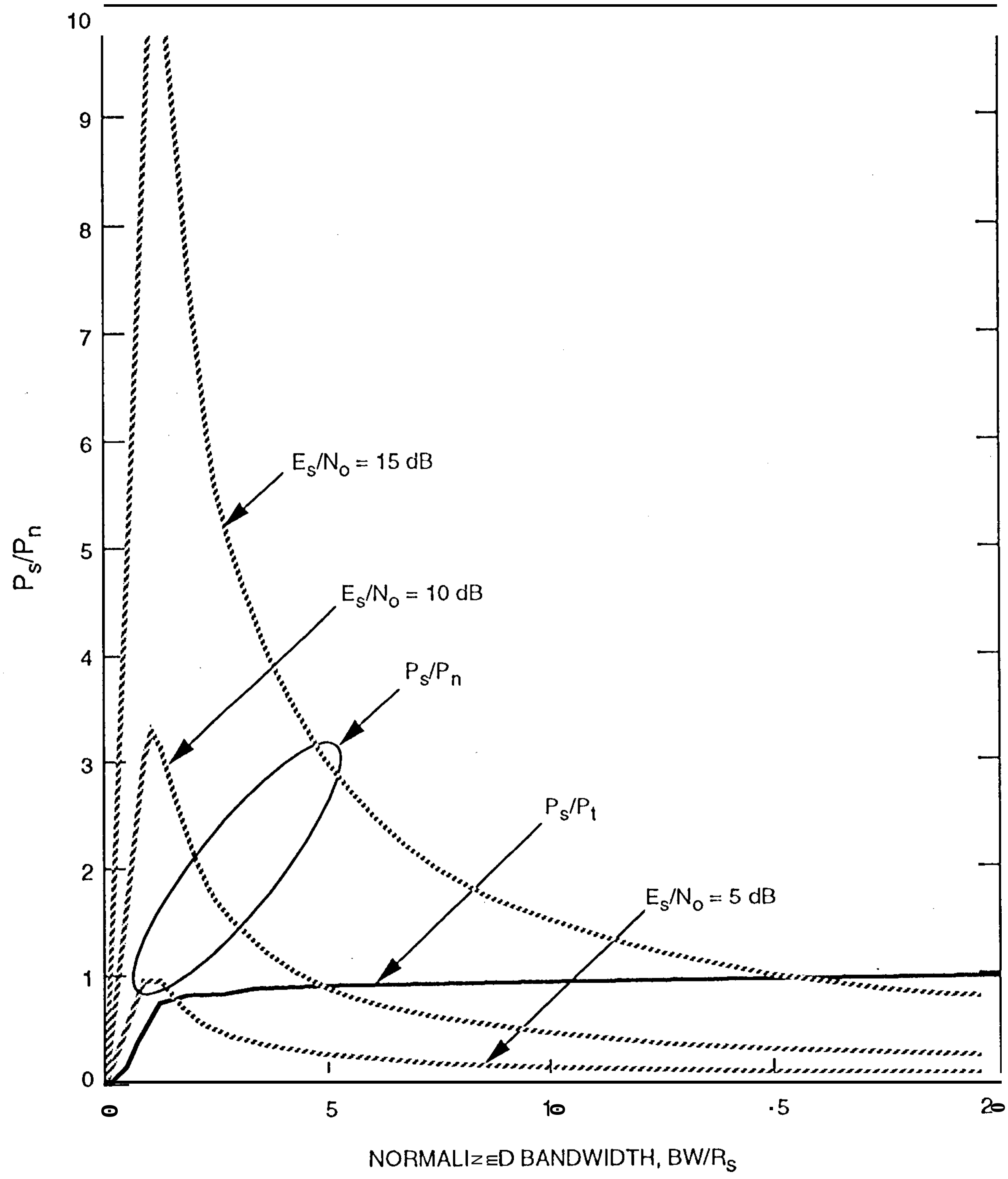

Figure 16. B SK/B in the Presence o Noise

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